July 1966

MATERIALS DATA HANDBOOK

Aluminum Alloy 6061

Edited by

John Sessler
Volker Weiss

Sponsored by

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

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SYRACUSE UNIVERSITY RESEARCH INSTITUTE
DEPARTMENT OF CHEMICAL ENGINEERING AND METALLURGY

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Contract No. NAS8-11345

DEPARTMENT OF CHEMICAL ENGINEERING AND METALLURGY
SYRACUSE UNIVERSITY, SYRACUSE, NEW YORK

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PREFACE

This Materials Data Handbook on the aluminum alloy 6061 was prepared by personnel and associates of the Department of Chemical Engineering and Metallurgy, Syracuse University, as part of a program sponsored by the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama.

It is intended that this Handbook present, in the form of a single document, a comprehensive summary of the materials property information presently available on the 6061 alloy.

The scope of the information included herein includes physical and mechanical property data at cryogenic, ambient and elevated temperatures, supplemented with useful information in such areas as material procurement, metallurgy of the alloy, corrosion, environmental effects, fabrication and joining techniques. Design data are presented, where available, and these data are complemented with information on the typical behavior of the alloy. The major source for the design data used is the Department of Defense document, Military Handbook - 5. "surrounding"

The Handbook is divided into twelve (12) chapters as outlined below:

Chapter		
	1	General Information
	2	Procurement Information
	3	Metallurgy
	4	Production Practices
	5	Manufacturing Practices
	6	Space Environment Effects
	7	Static Mechanical Properties
	8	Dynamic and Time Dependent Properties
	9	Physical Properties
	10	Corrosion Resistance and Protection
	11	Surface Treatments
	12	Joining Techniques

Information on the alloy is given in the form of Tables and Illustrations supplemented with descriptive text where deemed useful by the authors. Source references for the information presented are listed at the end of each chapter.

ACKNOWLEDGEMENTS

The "Materials Data Handbook, Aluminum Alloy 6061", was prepared by Syracuse University under Contract No. NAS8-11345 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The program was administered under the technical direction of the Propulsion and Vehicle Engineering Laboratory, Materials Division of the Space Flight Center with Mr. Melvin G. Olsen acting as project manager.

Acknowledgement is made to the following Syracuse University personnel and associates for their contributions to the program.

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John G. Sessler, Editor
Volker Weiss, Associate Editor

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TABULAR ABSTRACT

Aluminum 6061

TYPE:

Wrought, heat treatable aluminum alloy.

NOMINAL COMPOSITION:

Al-1.0Mg-0.6Si-0.25Cu-0.25Cr

AVAILABILITY:

Bare and clad sheet and plate, rod, bar, wire, tube, extruded shapes, pipe, forgings and forging stock.

TYPICAL PHYSICAL PROPERTIES:

Density	2.70 gr/cm^3 at 20C
Thermal Conductivity	0.41 cal-cm/sec cm^2C (O temper)
	0.37 cal-cm/sec cm^2C (T6 temper)
Thermal Expansion	(20-100C), 23.4 x 10^{-6} in/in/C
Specific Heat	0.23 cal/grC at 100C
Electrical Resistivity	1.51 microhm-inch (O temper)
	1.69 microhm-inch (T6 temper)

TYPICAL MECHANICAL PROPERTIES:

F_{tu}	18,000 psi (O temper)
	45,000 psi (T6 temper)
F_{ty}	8,000 psi (O temper)
	40,000 psi (T6 temper)
e(2 inch)	30 percent (O temper)
	17 percent (T6 temper)
E (tension)	10.0 x 10^6 psi

FABRICATION CHARACTERISTICS:

Weldability	Good (fusion) if proper procedures are used
	Good (resistance). Special practices required
Formability	Excellent in annealed condition. Also can be formed in T4 temper
Machinability	Excellent in T4 and T6 tempers

COMMENTS:

A versatile aluminum alloy having moderate strength and excellent resistance to corrosion.

SYMBOLS

a	One-half notch section dimension
A	Area of cross section; "A" basis for mechanical property values (Mil-Hdbk-5)
Å	Angstrom unit
AC	Air cool
AMS	Aerospace Material Specifications
Ann	Annealed
AUS	Austenitize
Av or Avg	Average
B	"B" basis for mechanical property values (Mil-Hdbk-5)
b	Subscript "bending"
bcc	Body centered cubic
BHN	Brinell hardness number
br	Subscript "bearing"
Btu	British thermal unit (s)
C	Degree (s) Centigrade
c	Subscript "compression"
CD	Cold drawn
CF	Cold finished
cm	Centimeter
c_p	Specific heat
CR	Cold rolled
CW	Cold worked
CVM	Consumable vacuum melted
D or Dia	Diameter
DPH	Diamond pyramid hardness
e	Elongation in percent
E	Modulus of elasticity, tension
E_c	Modulus of elasticity, compression
e/D	Ratio of edge distance to hole diameter
E_s	Secant modulus
E_t	Tangent modulus
ev	Electron volt (s)

F	Degree (s) Fahrenheit
f	Subscript "fatigue"
F_{bru}	Bearing ultimate strength
F_{bry}	Bearing yield strength
fcc	Face centered cubic
FC	Furnace cool
F_{cy}	Compressive yield stress
F_{su}	Shear stress; shear strength
F_{tu}	Tensile ultimate strength
F_{ty}	0.2% tensile yield strength (unless otherwise indicated)
G	Modulus of rigidity
HAZ	Heat affected zone in weldments
hcp	Hexagonal close pack
hr	hour (s)
HT	Heat treat
IACS	International annealed copper standards
in	inch
ipm	inches per minute
K	Stress intensity factor; thermal conductivity
K_c	Measure of fracture toughness (plane stress) at point of crack growth instability
K_{Ic}	Plane strain fracture toughness value
KSI or ksi	Thousand pounds per square inch
K_t	Theoretical elastic stress concentration factor
L	Longitudinal
lb	Pound
LT	Long transverse (same as transverse)
M	Bending moment
m	Subscript "mean"
Max	Maximum
MIL	Military
Min	Minimum
N	Cycles to failure
NSR	Notch strength ratio
NTS	Notch tensile strength

OQ	Oil quench
ppm	Parts per million
pt	Point
r	radius
RA	Reduction in area; Rockwell hardness A scale
RB	Rockwell hardness B scale
RC	Rockwell hardness C scale
ρ (rho)	Density
rpm	Revolutions per minute
RT	Room temperature
SA	Solution anneal
sec	second
S-N	S = stress; N = number of cycles
Spec	Specifications; specimen
ST	Solution treat; short transverse
T	Transverse
t	Thickness; Time, hour
Temp	Temperature
typ	Typical
Var	Variable
VHN	Vickers' hardness number
W	Width
WQ	Water quench

CHAPTER 1

GENERAL INFORMATION

1.1 Aluminum alloy 6061 is a heat treatable wrought alloy developed by the Aluminum Company of America (Alcoa) in 1935 as a general purpose structural alloy. The main alloying elements are magnesium and silicon and the alloy also contains small additions of copper, chromium, iron, zinc, manganese and titanium. This alloy is the most versatile of the wrought heat treatable alloys.

1.2 Aluminum 6061 combines the qualities of excellent resistance to corrosion and ease of fabrication with good mechanical properties. Its machinability rating is excellent and the alloy is readily welded by all conventional methods, when proper techniques are used, without lowering its corrosion resistance. The alloy also exhibits excellent brazing characteristics in all tempers. Alloy 6061 is available in the full commercial range of sizes for sheet, strip, plate, bar, rod, forgings, rolled shapes, extrusions, tubing, pipe, wire and rivets. Alloy is also available as Alclad sheet and plate, (Refs. 1.1, 1.2, 1.4).

1.3 Aluminum 6061 is used for many applications because of its versatility. Typical areas are marine applications, machinery parts, aircraft fairing, large trailer bodies, screw machine products, architectural applications, aircraft landing mats and furniture, (Refs. 1.1, 1.3, 1.4).

CHAPTER 1 - REFERENCES

1.1 "Alloy Digest - Aluminum 6061", Filing Code Al-3, Engineering Alloys Digest, Inc., (November 1952)

1.2 "Aerospace Structural Metals Handbook", Vol. II Non-Ferrous Alloys, V. Weiss and J.G. Sessler (Editors) ASD-TDR-63-741, (1963) Revised 1964 and 1965

1.3 Materials in Design Engineering, Materials Selector Issue, (Mid-October 1964)

1.4 "The Aluminum Data Book", Reynolds Metals Co., (1965)

CHAPTER 2

PROCUREMENT INFORMATION

2.1 General. Aluminum alloy 6061 is available in the full commercial range of sizes for sheet, strip, plate, rod, bar, forgings, tube, wire, extrusions and structural shapes. Detailed tables of standard sizes and tolerances for the various products available are given in Refs. 2.1 and 2.2.

2.2 Procurement Specifications. Specifications that apply to the 6061 alloy as of May 31, 1965 are listed in Table 2.2 for various products and tempers.

2.21 NASA Specifications.

2.211 MSFC-SPEC-144B, "Specification for Aluminum Alloy Forgings, Premium Quality, Heat Treated", dated March 31, 1964, Amendment 1, dated September 8, 1964. Prepared by George C. Marshall Space Flight Center (MSFC). Custodian: NASA-MSFC. Specification applies to 6061-T4, 6061 T6 and 6061-T652 forgings for parts used in critical applications.

2.3 Comparison of Specifications. Federal procurement specifications are applicable to 6061 extruded bar, rod, shapes and tube; rolled or drawn bar, rod, wire and shapes; bare sheet and plate; forgings, seamless drawn tube, rivet wire, nails, wire and staples. Military specifications apply to forgings, extruded or drawn pipe, structural shapes, aircraft hydraulic tubing, impact extrusions and floor plate. ASTM specifications apply to all wrought products except forging stock, aircraft quality tube, impact extrusions, rivets, floor plate and nails. AMS specifications cover all wrought products except pipe, structural shapes, welded tube, impact extrusions, rivets and rivet wire, floor plate and nails.

2.4 Major Producers of the Alloy (United States Only)

Aluminum Company of America
1501 Alcoa Building
Pittsburgh, Pennsylvania

Kaiser Aluminum and Chemical Sales, Inc.
919 North Michigan Avenue
Chicago, Illinois

Harvey Aluminum
General Offices
Torrance, California

Reynolds Metals Company
6601 West Broad Street
Richmond, Virginia

Olin-Mathieson Chemical Corporation
460 Park Avenue
New York, New York

2.5 Available forms, sizes, conditions and tolerance for various 6061 alloy products are given in detail in Refs. 2.1 and 2.2.

TABLE 2.2

Source	(Refs. 2.3, 2.4, 2.6, 2.7, 2.8)				
Alloy	Al6061				
Product	Temper	Military	Federal	ASTM	AMS
Bar, rod, shapes, tube (extruded)	0	-	QQ-A-200/8B	B221-65	4160
	T4	-	QQ-A-200/8B	B221-65	4161
	T6	-	QQ-A-200/8B	B221-65	4150C
	F, T42, T62	-	-	B221-65	-
	T4510, T4511	-	-	B221-65	-
	T6510, T6511	-	-	B221-65	-
Bar, rod, wire, shapes (rolled or drawn)	0	-	QQ-A-225/8B	B211-65	4115
	T4	-	QQ-A-225/8B	B211-65	4116A
	T6	-	QQ-A-225/8B	B211-65	4117A
	T42, T62	-	-	B211-65	-
	T451, T651	-	QQ-A-225/8B	B211-65	-
	T89, T94	-	-	B211-65	-
Sheet, plate (bare)	0	-	QQ-A-250/11C	B209-65	4025D
	T4	-	QQ-A-250/11C	B209-65	4026D
	T6	-	QQ-A-250/11C	B209-65	4027E
	T42, T62	-	-	B209-65	-
	T451	-	QQ-A-250/11C	B209-65	4043
	T651	-	QQ-A-250/11C	B209-65	4053
	F	-	QQ-A-250/11C	-	-
Sheet, plate (Alclad)	0	-	-	B209-65	4021B
	T4	-	-	B209-65	4022C
	T6	-	-	B209-65	4023C
	T42, T62	-	-	B209-65	-
	T451	-	-	B209-65	-
	T651	-	-	B209-65	4020
Pipe (extruded or drawn)	T6	MIL-P-25995	-	B241-65	-
	T4, T6	-	-	B345-55	-

PROCUREMENT SPECIFICATIONS

TABLE 2.2 (continued)

Source	(Refs. 2.3, 2.4, 2.6, 2.7, 2.8)				
Alloy	Al 6061				
Product	Temper	Military	Federal	ASTM	AMS
Clad pipe (extruded or drawn)	T6	-	-	B345-65	-
Forgings	T6	MIL-A-22771B	QQ-A-367F-1	B247-65	4127B
	T4	-	-	-	4146
Forging stock	T6	-	-	-	4127B
	T4	-	-	-	4146
Armor plate	-	MIL-A-46027C	-	-	-
Structural shapes	T4, T6	MIL-A-25994	-	B308-65	-
Tube, seamless (drawn)	0	-	WW-T-700/6C	B210-65	4079, 4080E
	T4	-	WW-T-700/6C	B210-65, B234-65	-
	T6	-	WW-T-700/6C	B210-65, B234-65	4082E
Tube, aircraft hydraulic	T4	MIL-T-7081C	-	-	4081A
	T6	MIL-T-7081C	-	-	4083D
Tube, round (welded)	0, T4, T6	-	-	B313-65	-
Impact extrusions	0, F, T4, T6	MIL-A-12545A	-	-	-
	T84	MIL-A-12545A	-	-	-
Rivets	T6	MIL-R-1150A-1	-	-	-
Rivet wire	0, H13, T6	-	QQ-A-430-1	B316-65	-
Floor plate	0, F, T4, T6	MIL-F-17132B	-	-	-
Nails, wire, staples	-	-	FF-N-105-2	-	-

CHAPTER 2 - REFERENCES

2.1 "Standards for Aluminum Mill Products", Seventh Edition, The Aluminum Association, (October 1964)

2.2 "Alcoa Aluminum Handbook", Aluminum Co. of America, (1962)

2.3 "Alcoa Product Data - Specifications", Section A12A, Aluminum Co. of America, (July 1963)

2.4 "1965 SAE Handbook", Society of Automotive Engineers, (1965)

2.5 "1963 Supplement to and Changes in Book of ASTM Standards, Part 2, Non Ferrous Metals Specifications, Electron Tube Materials, Semiconductors", Am. Soc. Test. Mets., (1963)

2.6 "SAE Aerospace Material Specifications", Soc. Automotive Eng., Inc., (Latest Index, February 15, 1965)

2.7 Department of Defense, "Index of Specifications and Standards", Part I, Alphabetical Listing, and Part II, Numerical Listing, (September 1964), Supplemented, (March 31, 1965)

2.8 ASTM Standards, Part 6, "Light Metals and Alloys", (October 1964)

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CHAPTER 3

METALLURGY

3.1 Chemical Composition

3.11 Nominal chemical composition of 6061, in percent, (Ref. 3.1).

Cu	0.25
Cr	0.25
Mg	1.0
Si	0.6
Al	Balance

3.111 Sheet and plate are available in the Alclad condition. Cladding material is Al 7072 alloy. Nominal composition of 7072 alloy, in percent, (Ref. 3.1).

Zn	0.8-1.3
Si + Fe	0.7
Mn	0.1 max
Cu	0.1 max
Mg	0.1 max
Others	
Each	0.05 max
Total	0.15
Al	Balance

The nominal cladding thickness per side is 5 percent of the total composite thickness for all sheet and plate thicknesses. The 6061 alloy is clad on both sides.

3.12 Chemical composition limits, in percent, (Ref. 3.1).

not in nominal listing

Si	0.40-0.80
Fe	0.7 max
Cu	0.15-0.40
Mn	0.15 max
Mg	0.8-1.2
Cr	0.15-0.35
Zn	0.25 max
Ti	0.15 max
Others	
Each	0.05 max
Total	0.15 max
Al	Balance

3.13 Alloying Elements. Magnesium and silicon are the primary alloying elements, with copper added for extra strength and chromium for extra strength, grain refinement, and improved corrosion resistance. The primary precipitation hardening agent is Mg_2Si. $CuAl_2$ also contributes to a limited extent to hardening. Ternary phase diagrams of Al-Mg-Si are shown in Figs. 3.131, 3.132 and 3.133, (Ref. 3.4). The binary Al-Cu system is shown in Fig. 3.134 and the binary Al-Cr system in Fig. 3.135, (Ref. 3.5). The important eutectic temperatures are Al-Cu, 548C, and Al-Mg_2Si, 595C, (Refs. 3.4 and 3.5). An excess of Si lowers the corrosion resistance appreciably, (Ref. 3.3). In general, the low total alloying content gives this alloy many characteristics of commercially pure aluminum, such as good corrosion and stress corrosion resistance and weldability (including fusion welding), (Ref. 3.6). Further corrosion protection is provided by cladding, see Section 3.111.

3.2 Strengthening Mechanisms

3.21 General. The alloy is strengthened by precipitation hardening and cold work. The precipitation hardening mechanisms are evident from the phase diagrams, Figs. 3.131 to 3.135. Because of the low alloying content, the solution treated condition is very stable, (Ref. 3.6). On heating to the aging temperature, precipitation occurs in the form of submicroscopic particles, which represent obstacles to the plastic flow and thus cause hardening. The alloy can also be hardened by cold-work, a general property of all aluminum alloys related to crystal structure and stacking fault energy. Various processes utilize the effect of both operations, i.e. cold working in the solution treated condition and subsequent aging, as well as cold working after aging.

3.22 Heat Treatment. Recommended heat treating procedures for the 6061 alloy are given below.

3.221 Annealing (O Condition). The annealing treatment is essentially an overaging treatment. Heat to 413C, hold 2 to 3 hours, followed by slow cool (28C/hr) to 260C, (Ref. 3.7). Intermediate anneals for the removal of cold work should be performed at 343C. Time and cooling rate are not critical, (Ref. 3.7).

3.222 Solution Treatment, (Ref. 3.11).

Bare Products, (except forgings):
Heat to 521 to 543C, hold as per Table 3.22, followed by rapid cold water quench.

Clad Sheet and Plate:

Heat to 516 to 538C, hold as per Table 3.22, followed by rapid cold water quench.

Forgings:

Heat to 516 to 543C, hold as per Table 3.22, followed by rapid cold water quench.

Heating may be in salt bath or air furnace. Recommended soaking times are given in Table 3.22, (Ref. 3.11).

3.223 Precipitation Treatments (Aging), (Ref. 3.11).

Natural Age to T4 Condition (all products except forgings):

Hold as-quenched material at room temperature for 96 hours.

Artificial Age to T6 Condition (all products):

Heat T4 material to 171C to 182C, hold 7.5 to 8.5 hours. The cooling rate from the aging temperature is not critical. The designation is T62 if solution and aging treatments are performed by the user.

3.224 Cold work and combined treatments, together with solution and aging treatments for various products, are listed in Table 3.224.

3.3 Critical Temperatures. Melting range is 582 to 649C, (Ref. 3.10). The oxidation resistance is generally good until the melting temperature is approached.

3.4 Crystal Structure. Face-centered-cubic. The lattice parameter for pure Al is $a_o = 4.0491$, (Ref. 3.10).

3.5 Microstructure. The as-cast structure, with and without preheating the ingot for homogenization, is shown in Figs. 3.51 and 3.52, respectively. The annealed structure (O Condition) is shown in Fig. 3.53. The solution treated and aged structure is shown in Fig. 3.54. For these structures, the specimen was swabbed with an etching reagent consisting of 0.5 percent hydrofluoric acid in water. The difference in appearance of the microstructure between natural and artificial aging can be developed by immersion etching with 2.5 percent Hf and 5 percent H_2SO_4 in water, see Fig. 3.55. Recrystallization during heat treatment can also be readily recognized after the use of the hydrofluoric-sulfuric acid etch, Fig. 3.56, (Ref. 3.8). Ref. 3.9 is recommended as an excellent source of information on the identification of constituents in aluminum alloys.

Section 3.5 and associated [illegible]

Dick Raring Comment

3.6 Metallographic Procedures: In general, mechanical polishing is preferred to electropolishing, especially where larger microconstituents are present and the material is relatively soft, as objectionable relief effects produced by the electrolytic polishing technique may cause a misinterpretation of the microstructure, (Ref. 3.8). For homogeneous alloys, and for those conditions containing only finely dispersed particles, the electrolytic method is excellent. Preparatory polishing on metallographic polishing papers 0 to 000 should be performed wet with a solution of 50g paraffin in 1 liter kerosene to keep the specimen bright and avoid imbedding of grinding compound particles into the soft specimen surface. Rough polishing on a "kitten's ear" broadcloth at 250 to 300 RPM with heavy magnesium oxide powder is recommended, (Refs. 3.4 and 3.9).

An alternate and popular method consists of the following steps:

(a) Wet polishing (flowing water with 240 grit silicon carbide paper at approximately 250 RPM.

(b) Wet polishing with 600 grit silicon carbide paper at approximately 250 RPM.

(c) Polishing with 9 micron diamond paste on nylon cloth at 150 to 200 RPM using a mild soap solution for lubrication.

(d) Final polish on a vibratory polisher using a microcloth containing a slurry of methyl alcohol and 0.1 micron aluminum oxide powder. A slurry of 0.1 micron aluminum oxide powder in a 10 percent solution of glycerine in distilled water may also be used for this step.

Etching reagents have to be suited to the objective of the study. Keller's etch reveals microstructural details and grain boundaries satisfactorily. A 10 percent solution of NaOH gives better detail of the microstructural constituents but does not delineate the grain boundaries. Study of the "as polished" surface prior to etching may also give valuable information on the types of constituents present, especially when attention is paid to the colors of the various particles. Macroscopic studies for cracks, gross defects, forging lines and grain structure should be made with the following etching solutions: 10% NaOH (cracks, gross defects), Tucker's etch, modified Tucker's etch and Flick's etch from ASM Table 1, p. 95, (Ref. 3.4). These etching solutions for revealing the macrostructure are given in Table 3.61. Suggested etching reagents for revealing microstructure are presented in Table 3.62.

SOAKING TIME FOR SOLUTION TREATMENT OF ALL WROUGHT PRODUCTS

TABLE 3.22

Thickness (inches) [2]	Soaking time (minutes) [1]			
	Salt bath [3]		Air furnace [4]	
	(min)	(max) (alclad only) [5]	(min)	(max) (alclad only) [5]
0.016 and under	10	15	20	25
0.017 to 0.020 incl.	10	20	20	30
0.021 to 0.032 incl.	15	25	25	35
0.033 to 0.063 incl.	20	30	30	40
0.064 to 0.090 incl.	25	35	35	45
0.091 to 0.125	30	40	40	50
0.126 to 0.250 incl.	35	45	50	60
0.251 to 0.500 incl.	45	55	60	70
0.501 to 1.000 incl.	60	70	90	100
1.001 to 1.500 incl.	90	100	120	130
1.501 to 2.000 incl.	105	115	150	160
2.001 to 2.500 incl.	120	130	180	190
2.501 to 3.000 incl.	150	160	210	220
3.001 to 3.500 incl.	165	175	240	250
3.501 to 4.000 incl.	180	190	270	280

[1] Longer soaking times may be necessary for specific forgings. Shorter soaking times are satisfactory when the soak time is accurately determined by thermocouples attached to the load.

[2] The thickness is the minimum dimension of the heaviest section.

[3] Soaking time in salt-bath furnaces should be measured from the time of immersion, except when, owing to a heavy charge, the temperature of the bath drops below the specified minimum; in such cases, soaking time should be measured from the time the bath reaches the specified minimum.

[4] Soaking time in air furnaces should be measured from the time all furnace control instruments indicate recovery to the minimum 9th process range.

[5] For alclad materials, the maximum recovery time (time between charging furnace and recovery of furnace instruments) should not exceed 35 minutes for gages up to and including 0.102 inch, and 1 hour for gages heavier than 0.102 inch.

(Ref. 3.11)

TEMPERS AND TREATMENTS FOR BARE AND CLAD PRODUCTS

TABLE 3.224

Sheet	Plate	Rod, Bar, Wire (Rolled or CF)	Rod, Bar, Shapes, Tube (extruded)	Tube (Drawn)	Pipe	Description of Treatment to Produce Indicated Temper
			F			As fabricated
O*	O*	O	O	O		413C, 2 to 3 hr, cool 28C/hr to 260C
T4*	T4*	T4	T4	T4		See Chapter 3, Section 3.222
T42*	T42*	T42	T42	T42		T4 heat treated by the user
	T451*	T451				T4 + stress relief by stretching (a)
			T4510			Stress relief by stretching (b)
			T4511			Stress relief by stretching (c)
T6*	T6*	T6	T6	T6	T6	See Chapter 3, Section 3.223
			T62			T6 heat treated by the user
	T651*	T651				T6 + stress relief by stretching (a)
			T6510			Stress relief by stretching (b)
			T6511	T6511		Stress relief by stretching (c)
H12						Cold work to 1/4 hard condition
		T89				ST + CW + artificial age
		T93				ST + artificial age + CW
		T94				ST + artificial age + CW
		T913				ST + artificial age + CW

TEMPERS AND TREATMENTS FOR BARE AND CLAD PRODUCTS

TABLE 3.224 (cont'd)

Rivet Wire and Rod	Die Forgings	Hand Forgings	Forging Stock	Structural Shapes (Rolled or Extruded)	Rolled Rings	Description of Treatment to Produce Indicated Temper
			F			As fabricated
O						413C, 2 to 3 hr, cool 28C/hr to 260C
				T4		See Chapter 3, Section 3.222
	T6	T6		T6	T6	See Chapter 3, Section 3.223
					T652	T6, Stress-relieved by compressing
H13						Cold worked to 3/8 hard condition

* 6061 Alclad also

(a) 1.5 to 3 percent permanent set for sheet and plate
1 to 3 percent permanent set for rod, bar, shapes and tube
0.5 to 3 percent permanent set for drawn tube

(b) No further straightening after stretching

(c) Minor straightening after stretching to comply with standard tolerances

(Refs. 3.2 and 3.7)

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ETCHING SOLUTIONS FOR REVEALING MACROSTRUCTURE

TABLE 3.61

Source	Ref. 3.4		
Solution	Concentration (a)		Specific Use
Sodium Hydroxide	NaOH	10 g	For cleaning surfaces, revealing unsoundness, cracks and gross defects
	Water	90 ml	
Tucker's	HCl (conc.)	45 ml	For revealing structure of castings, forgings, etc.
	HNO_3 (conc.)	15 ml	
	HF (48%)	15 ml	
	Water	25 ml	
Modified Tucker's	HCl (conc.)	10 ml	For revealing structure of all castings and forgings except high silicon alloys.
	HNO_3 (conc.)	10 ml	
	HF (48%)	5 ml	
	Water	75 ml	
Flick's	HCl (conc.)	15 ml	For revealing grain structure of duralumin type alloys. Surface should be machined or rough polished
	HF (48%)	10 ml	
	Water	90 ml	

(a) All of these solutions are used at room temperature.

ETCHING REAGENTS FOR REVEALING MICROSTRUCTURE

TABLE 3.62

Source No.	Composition	Uses	Remarks
	Ref. 3.8		
1	HF (conc.) 0.5ml H_2O 99.5ml	General microstructure	Swab with soft cotton for 15 seconds
2	NaOH 1g H_2O 99ml	General microstructure	Swab with soft cotton for 10 seconds
3	NaOH 10g H_2O 90ml	General microstructure (micro and macro)	Immerse 5 seconds at 160F, rinse in cold water
4	Keller's (conc.) HF (conc.) 10ml HCl (conc.) 15ml HNO_3 (conc.) 25ml H_2O 50ml	General microstructure (micro and macro) for copper bearing alloys)	Use concentrated for macroetching; dilute 9 to 1 with water for microetching
5	HF 5ml H_2SO_4 10ml H_2O 185ml	Grain structure,solution, treated 6061. Will show difference between T4 and T6 temper	Etch 30 seconds for grain boundary of T4 material; 60 seconds for T6 material. Also extent of recrystallization.

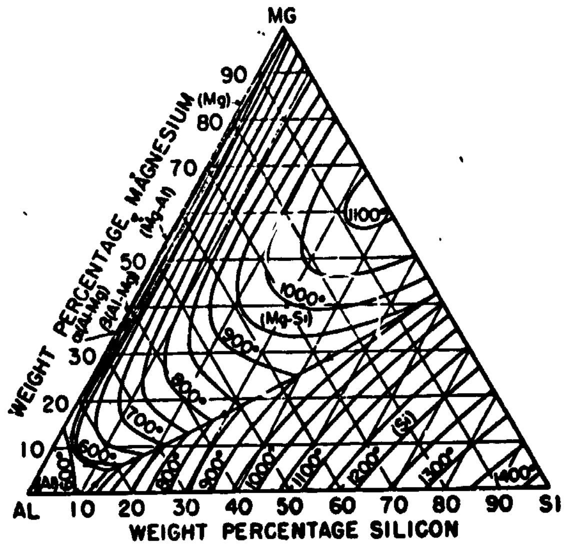


FIG. 3.131 LIQUIDUS SURFACE OF ALUMINUM-MAGNESIUM-SILICON SYSTEM

(Ref. 3.4)

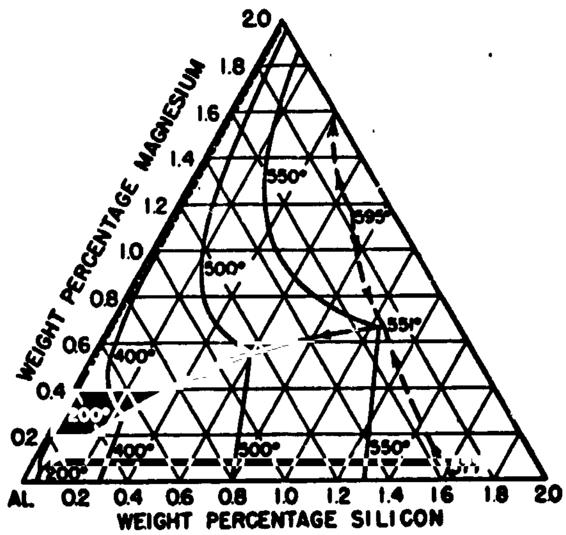


FIG. 3.133 SOLVUS SURFACE IN ALUMINUM CORNER OF ALUMINUM-MAGNESIUM-SILICON SYSTEM

(Ref. 3.4)

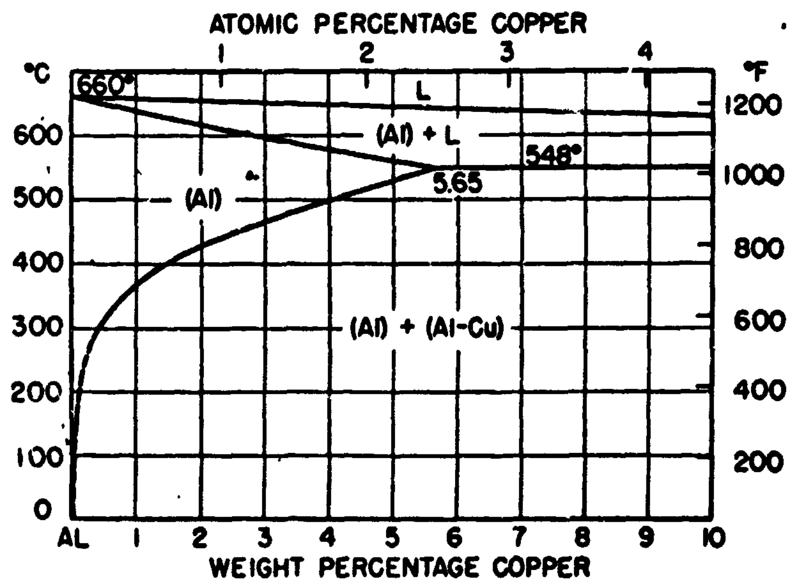


FIG. 3.134 ALUMINUM-COPPER SYSTEM

(Ref. 3.5)

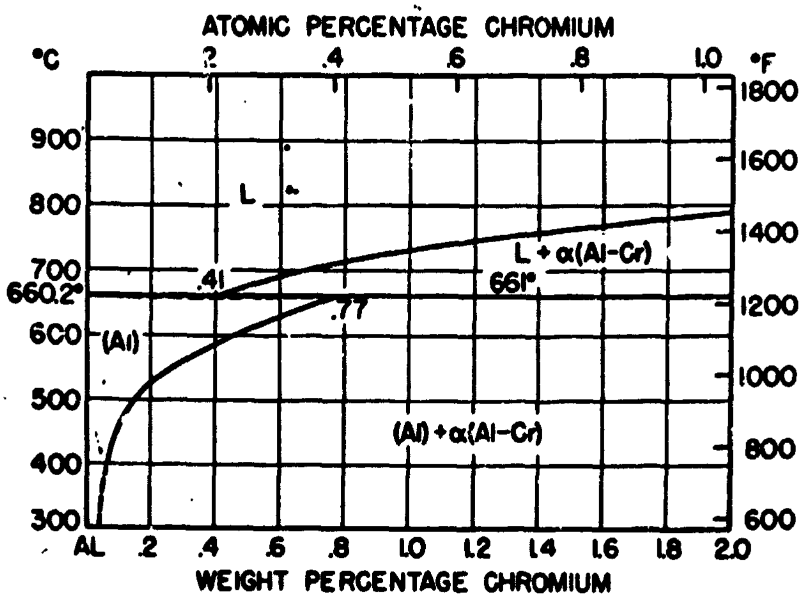


FIG. 3.135 ALUMINUM-CHROMIUM SYSTEM

(Ref. 3.5)

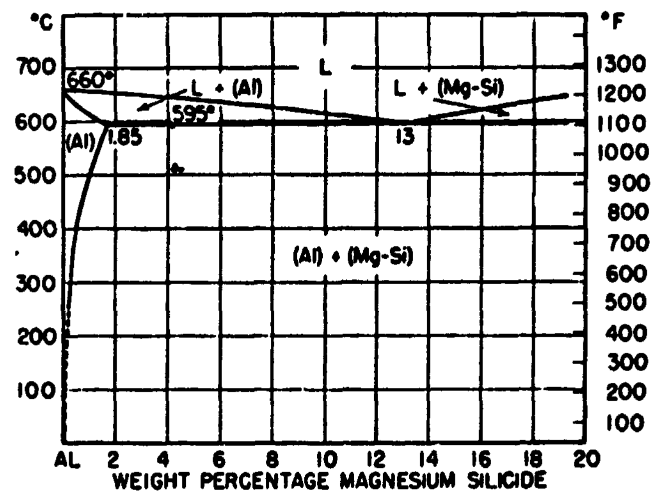
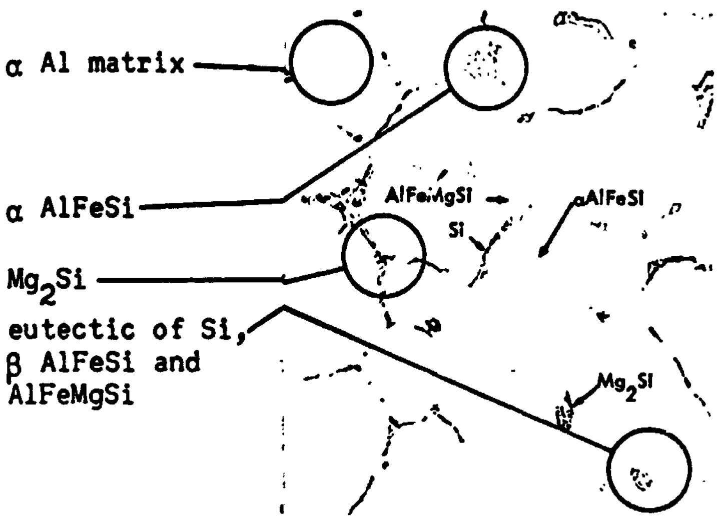


FIG. 3.132 BINARY SECTION, ALUMINUM-MAGNESIUM-SILICIDE

(Ref. 3.4)

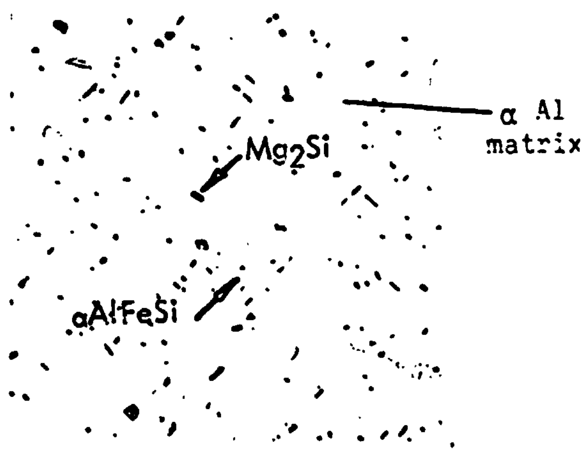
ALUMINUM-MAGNESIUM-SILICON SYSTEM,
ALLOY 6061



Etching Reagent No. 1 (Table 3.2) 500X

FIG. 3.51 AS CAST STRUCTURE

(Ref. 3.8)



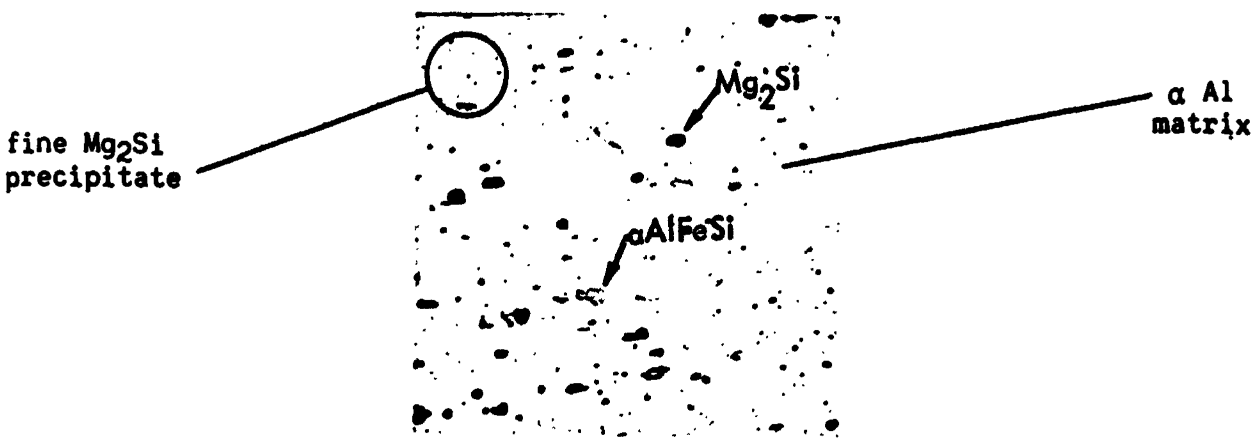
Etching Reagent No. 1 (Table 3.2) 500X

FIG. 3.52 PREHEATING THE INGOT HOMOGENIZES THE STRUCTURE

(Ref. 3.8)

Courtesy Kaiser Aluminum and Chemical Corp.

ALUMINUM-MAGNESIUM-SILICON SYSTEM,
ALLOY 6061



Etching Reagent No. 1 (Table 3.2) 500X

FIG. 3.53 THE ANNEALED STRUCTURE

(Ref. 3.8)

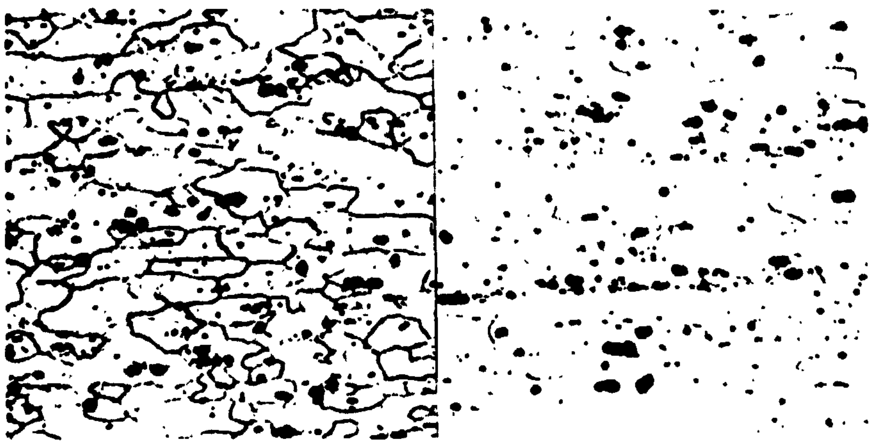
Etching Reagent No. 1 (Table 3.2) 500X

FIG. 3.54 SOLUTION HEAT TREATED AND AGED

(Ref. 3.8)

Courtesy Kaiser Aluminum and Chemical Corp.

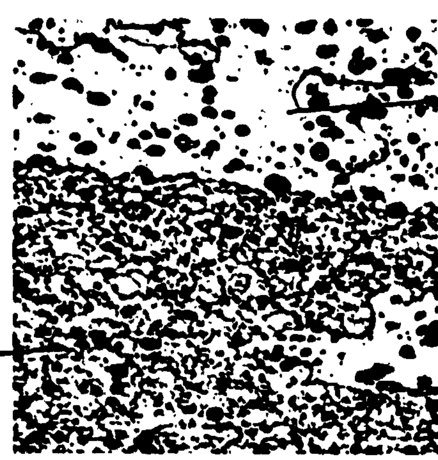
ALUMINUM-MAGNESIUM-SILICON SYSTEM, ALLOY 6061



T4 T6

Etching Reagent No. 5 (Table 3.2) 500X

FIG. 3.55 NATURAL AGING (T4) AND ARTIFICIAL AGING (T6) (Ref. 3.8)



Etching Reagent No. 5 (Table 3.2) 250X

FIG. 3.56 RECRYSTALLIZATION DURING HEAT TREATMENT (Ref. 3.8)

Courtesy Kaiser Aluminum and Chemical Corp.

CHAPTER 3 - REFERENCES

3.1 "Alcoa Aluminum Handbook", Aluminum Company of America, (1962)

3.2 "Standards for Wrought Aluminum Mill Products", Eighth Edition, The Aluminum Association, New York, (September 1965)

3.3 J. A. Nock, Jr., "Commercial Wrought Aluminum Alloys", (in book), Physical Metallurgy of Aluminum Alloys, American Society for Metals (1958)

3.4 W. L. Fink et al., "Physical Metallurgy of Aluminum Alloys", American Society for Metals, (1958)

3.5 E. H. Wright and L. A. Willey, "Aluminum Binary Equilibrium Diagrams", Alcoa Technical Paper No. 15, (1960)

3.6 W. H. Dennis, "Metallurgy of the Non-Ferrous Metals", Sir Isaac Pitman & Sons, Ltd., (1960)

3.7 "The Aluminum Data Book", Reynolds Metals Co., (1965)

3.8 J. P. Vidosic, "Study of Phase Identification in Steel and Aluminum Alloys", Georgia Institute of Technology, Final Report, Project No. A-641, NASA Contract NAS8-5117, (September 1963)

3.9 F. Keller and G. W. Wilcox, "Identification of Constituents of Aluminum Alloys", Technical Paper No. 7, Aluminum Company of America, (1942)

3.10 "Metals Handbook", Eighth Edition, Vol. I, American Society for Metals, Metals Park, Novelty, Ohio, (1961)

3.11 Military Specification, "Heat Treatment of Aluminum Alloys", MIL-H-6088C, (October 1962)

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CHAPTER 4

PRODUCTION PRACTICES

4.1 General. In the United States, aluminum and its alloys are produced from an ore of impure hydrated aluminum oxide known as "bauxite". Important sources of bauxite are located in Arkansas, Dutch Guiana and Jamaica. The impure ore is converted into pure aluminum oxide (alumina) through a series of chemical processes. Oxygen is removed from the alumina by smelting in carbon-lined electric furnaces known as reduction pots. Pure molten aluminum is deposited at the bottom of the pot, and is periodically siphoned off and poured into molds to form "pigs" and "sows". A separate furnace operation is used to form "alloy pig" from the pure aluminum by the addition of alloying elements and this metal is cast into ingots for further processing, (Ref. 4.1).

For the 6061 alloy, the major alloying elements are magnesium and silicon with smaller additions of chromium and copper. Generally, this phase of production practice involves the melting, alloying and casting of large 20,000 to 50,000 pound ingots, carefully controlled. After the ingots are scalped and preheated in vertical electric soaking pits, they are ready for further processing to a particular form of product.

4.2 Manufacture of Wrought Products

4.21 Bar and rod are normally produced by hot rolling or extruding. Cold finished bar and rod are produced by hot working to a size slightly larger than specified and reducing to final dimensions by cold working. A better surface finish and closer dimensional tolerances are obtained in this manner, (Ref. 4.2).

4.22 A similar process is used to produce rolled structural shapes; special rolls being required. Finishing operations include roller or stretch straightening, and heat treatment.

4.23 Roll form-shapes are produced by passing strip through a series of roller dies. Each successive pair of rolls cause the work to assume a cross-section shape more nearly approaching that desired. The final desired shape is produced at the last pair of rolls.

4.24 Plate is produced by hot rolling of ingots to slabs (approximately 60 percent reduction), usually in a 4 high reversible mill. The slabs are then further reduced 50 percent in a reversible 2 high mill. The last stage of hot rolling is done in a hot reversing mill, where the plate is progressively rolled to the final hot mill dimensions. Plate may be subjected to "stress relief" stretching (about 2 percent permanent set) to improve flatness and reduce warpage upon machining. It is then sheared or sawed to the required dimensions, (Ref. 4.2).

4.25 Sheet is usually produced from plate by cold rolling to final sheet thickness, followed by trimming, tempering, heat treating stretching and other finishing operations. Alclad sheet and plate are made by cladding bare material with aluminum alloy 7072 (See Chapter 3, Section 3.111).

4.26 Wire is produced by drawing rod through a series of progressively smaller dies to obtain the desired dimensions.

4.27 Extrusions are produced by subjecting re-heated cast billets to enough pressure to force the metal to flow through a die orifice, forming a product whose cross-section shape and size conforms to that of the orifice. Speeds, pressures and temperatures must be closely controlled to insure uniform quality of extruded products.

4.28 Tube is produced by extruding, by drawing or by welding. Extruded tube is forced thru an orifice as described in 4.27. A die and mandrel are used. Drawn tube is manufactured by a cold process which is similar to drawing bar and rod. A mandrel is used with one end fixed and a bulb attached to the other end. The tube is drawn over the mandrel bulb and through a die at the same time. Welded tube is produced by slitting coil stock into strips and passing the strips through a series of rolls to form tube. The longitudinal seam is welded as the tube leaves the last roll forming station.

4.29 Forgings are made by pressing (press forging) or hammering (drop forging). Relatively heavy equipment is required since aluminum is not as plastic at its forging temperature as steel. Aluminum forgings compare favorably with structural steel in unit strength at about one-third the weight. With comparable strength and with a lower elastic modulus, aluminum alloys have a much higher impact-energy-absorbing capacity than mild steel.

4.3 Available Tempers, (Ref. 4.4).

4.31 Aluminum alloy 6061 products are available from producers of the alloy in the following tempers:

F.... As fabricated. Applies to products which acquire some temper from shaping processes not having special control over the amount of strain hardening or thermal treatment. For wrought products, there are no mechanical property limits.

0 .... Annealed (recrystallized). Applies to the softest temper of wrought products.

T4.... Solution heat treated and naturally aged to a substantially stable condition. (Designated T42 if performed by the user).

T6.... Solution treated and artificially aged. (Designated as T62 if performed by the user).

T451.. and T651 Stress relieve material by stretching the following amounts of permanent set after solution treatment:

Plate	1.5 to 3%
Rod, bar, shapes extruded tube	1.0 to 3%
Drawn tube	0.5 to 3%

Applies directly to plate, rolled or cold-finished rod and bar and drawn tube. These products receive no further straightening after stretching. T451 products are naturally aged after stretching and T651 products are artificially aged after stretching.

H12... Strain hardened to 1/4 hard condition to obtain desired mechanical properties with no supplementary thermal treatment. Applies to sheet products.

H13... Strain hardened to a condition midway between 1/4 and 1/2 hard conditions to obtain desired properties without supplementary thermal treatment. Applies to rod and rivet wire.

T9.... Solution heat treated, artificially aged and then cold worked to improve strength. Applies to wire products.

4.4 Casting of Alloy Ingots

4.41 Metal for wrought products is alloyed in large 10 to 25 ton double hearth furnaces, carefully controlled and instrumented. The direct chill (DC) method is generally usea for casting these ingots. Molten metal is poured into a mold and a hydraulic piston descends slowly as the metal solidifies. Water is sprayed on the outside of the mold to promote rapid solidification. Additional processing may include scalping (machining of outside surfaces) or homogenizing, (Refs. 4.2 and 4.3).

CHAPTER 4 - REFERENCES

4.1 "Kaiser Aluminum Sheet and Plate Product Information", Second Edition, Kaiser Aluminum and Chemical Sales, Inc., (January 1958)

4.2 "The Aluminum Data Book, Aluminum Alloys and Mill Products", Reynolds Metals Co., (1958)

4.3 "Alcoa Aluminum Handbook", Aluminum Co. of America, (1962)

4.4 The Aluminum Association, "Standards for Aluminum Mill Products", Eighth Edition (September 1965)

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CHAPTER 5

MANUFACTURING PRACTICES

5.1 General. This heat-treatable alloy is one of the silicon and magnesium series which combines medium strength, excellent corrosion resistance, good weldability, and low cost, (Ref. 5.2). It is available bare and in the Alclad condition. It is used in heavy-duty structures where corrosion resistance is needed; in marine, railroad car, furniture, and pipeline applications; for aircraft landing mats, pontoon boats, etc.

It is produced in all wrought forms and is often employed for elevated temperature service in the form of extrusions, tubular products or forgings. In aerospace flight vehicles, 6061 has been used for storage and handling equipment for red and white fuming nitric acids, the common oxidizers for rocket motors. For commercial transports, water storage tanks are often made of Clad 6061 to improve resistance to corrosion, (Ref. 5.6).

5.2 Forming

5.21 Sheet and plate. The relative formability of 6061 is excellent and not only does it have the usual formability of heat-treatable alloys in the "O" condition but it also is adaptable to rather severe forming operations in the T4 temper, (Ref. 5.4). The relative excellence for formability as compared with other heat-treatable alloys can be noted in Table 5.21.

5.211 Cold forming. The formability of alloy 6061 sheet and plate is directly related to the temper, strength and ductility. As with other aluminum alloys, high elongation as well as considerable spread between yield and ultimate strength will be indicative of good formability. In the annealed state the forming quality is similar to 1100-O and 3003-O; in the heat-treated and heat treated plus aged tempers it forms more nearly like 1100 in the hard temper, (Ref. 5.5). The simplest and most widely used forming method is probably that of bending. The ease of bending is indicative of most other forming operations. Table 5.211 indicates the ease of forming in terms of recommended minimum bend radii, as a function of temper and sheet and plate thickness, using typical mechanical properties of 0.100 inch sheet. In general, severe forming and drawing operations should be done with annealed stock and with clean tools free of scratches. T6 properties can be obtained in parts formed in the T4 temper by artificial aging after forming. The T4 temper is obtained by solution treatment at 970F followed by a water quench. Forming is rather easily performed on material in this temper. Reheating to 320F for 16 to 20 hours, or for a lesser time of 6 to 10 hours at 350F, produces the T6 temper.

Aluminum sheets are normally formed using operations such as

1. Bending
2. Flanging
3. Rolling
4. Dra ing
5. Pressing
6. Stretching
7. Embossing
8. Coining
9. Stamping
10. Spinning
11. Contour Forming
12. Bulging and Expanding
13. Beading and Roll Flanging
14. Necking
15. Curling

The factors influencing bending of 6061 sheet, as spelled out previously, also influence the fourteen other forming operations in the same general manner. Because of the lower modulus of elasticity of aluminum compared with steel, a much greater "springback" is expected and indeed is encountered. Over-forming is the common way of correcting the tendency. In addition, reducing the bend radius, increasing sheet thickness, forming at elevated temperatures, and increasing the total amount of plastic deformation will decrease the extent of springback. Alloy 6061 sheets can be formed to many shapes by drawing and this is the most extensively employed mass production method. Depending upon the desired shape, the part may be produced in one draw or in some cases the reduction is accomplished in successive draws using inter ediate annealing to avoid exhausting the ductility and introducing crack . Deep draws normally employ male and female metal dies. Forming in rubber (Guerin Process) for relatively shallow parts is a method where several thin layers of rubber are confined in a pad holder or retainer made of steel or cast iron. A descending ram, on which this holder is mounted, causes the aluminum sheet to be compressed against a form block to make the required part. If the aluminum is made to flow against a female die using fluid pressures behind a rubber diaphragm, the method is known as "hydroforming". Spinning and high energy rate methods have also been successful.

Alloy 6061 has been used for some recent applications such as the Saturn cold plate and the LEM cold plate. Refrigeration ducts and engine nacelle frames also have been formed from the alloy producing parts which have been very thin compared to the surface area, (Ref. 5.7). Upon conventional heat-treatment by quenching from above 900F into cold water severe distortion may be encountered in thin sections. The usual approach is to straighten or correct parts afterward and this is normally possible. However, there are instances in which parts must be scrapped because they are beyond correction. By utilizing liquid nitrogen as a quenching medium, the distortion is minimized and many hours of process time are eliminated.

5.212 Hot forming. When it is difficult to form heat treated 6061 alloy by conventional methods, hot forming may be used. Maximum recommended reheating periods are shown in Table 5.212. Lesser heat treatment times may give satisfactory results. Although formability at higher temperatures is easier, excessive heating should not be used due to strength loss.

5.22 Shapes, tubes and pipes. Either extrusion or rolling can be used to produce aluminum shapes. The standard shapes are I-beams, H-beams, channels, angles, tees and zees. The relative formability of alloy 6061 as tubes or extrusions can be noted in Table 5.22. As has been pointed out in the section discussing sheet and plate material, better formability can be obtained in the softer tempers and again the precautions of the previous section apply. Sections in the O temper are bent and formed more easily than those in the T4 and T6 heat-treated tempers, the last being the most difficult.

Stretching, wiping or rolling are general methods used to form shapes and tubes. Sheets, shapes and tubes are stretch formed by clamping at one end and pulling or stretching over a single male die so as to exceed the elastic limit. The metal section takes the shape of the die by stretching more in the heavier curvature areas than in the shallower ones. When working exceptionally thin-wall round, square, or rectangular tube on small radii, it is necessary to add a wiper and a flexible mandrel to provide extra support for the tube at the point of bending. Rolls can also be used for the forming, using dies to form the contours.

5.23 Forging. The aluminum alloy 6061 is the most versatile of the heat-treatable alloys. It can be forged without difficulty and is the most resistant to atmospheric and chemical corrosion of any of the aluminum forging alloys, (Ref. 5.8). The yield strength of 6061-T6 is almost as high as that of 2024-T4. Machinability and strength-to-weight ratio are fair. Strength at room temperature is moderate. Forgings are made using either the open die or closed die methods and by impact or pressure. Prototype or other few-of-a kind needs for aluminum parts usually do not warrant the cost of forging dies. Small runs are made using the hand forging open die techniques where the heated stock is worked between flat or simple dies that impose little or no lateral confinement on the material. Hand forgings over a ton in weight can be made. Hand forgings are provided in various tempers which are defined in Table 5.231.

As in all forgings there is grain flow in 6061 which is characteristic of the forging process. The resultant grain pattern results in anisotropy of properties and this must be considered for property evaluations. The process for most production forgings starts with the stock which can vary from 3/8 inch to 4 inch square stock, and rectangles from 3/8 inch for the minimum dimension to as much as 10 inches on the maximum dimension. Conditioning to remove localized surface defects is permitted at this point.

The stock is carefully heated in the range of 600 to 900F. The relative forgeability of 6061, as a function of the forging temperature relative to other aluminum alloys, can be seen in Fig. 5.232. The excellence of this alloy for forging can be noted. Oil-tank shells for aircraft were forged with a drop hammer from 5052-O alloy. A 60 percent rejection rate encountered with this alloy was reduced to one third by changing the part to 6061-0, (Ref. 5.6). The mechanical properties are a function of the forging direction as well as the size of the hand forging. Fig. 5.233 shows the test bar orientation as a function of the principal directions. Large production runs are made using closed dies. Either drop forging or press forging machinery is used. After preheating, the stock is formed in one step or in the case of complicated parts in several operations which may involve reheating. Dies in the forging operation are heated with auxilliary gas or electric heaters. The flash resulting from excess metal over-filling the mold is removed by hot or cold trimming, sawing or grinding.

Holes in the forging are pressed to produce "punchouts" in the forging. Sometimes the punchout is combined with the trim operation. Very close tolerances can be met in a standard forging by die coining (cold) to precise dimensions, usually within a few thousands of an inch.

Straightening after heat treatment is often a required operation. Templates combined with indicators and other gages are used to determine the out-of-tolerances. Straightening ranges from hand straightening to "cold restrike" operations. The forgings are inspected for grain flow, mechanical properties, dimensions and ultrasonic soundness.

5.3 Machining

5.31 Conventional machining. The aluminum alloy 6061 is readily machined in all conventional machining operations. The highest machinability is obtained in the hardest temper. In the softer tempers the alloy tends to be somewhat gummy and is not as machinable. Hand forgings of 6061 which require a large amount of metal removal by roughing out before heat treatment should be machined in the F temper. In those cases where hand forgings are to be machined to very close dimensions with the additional requirement for a good surface condition, the T4 temper yields optimum results. Small hand forgings can be machined successfully in the T6 temper.

It is difficult to produce a precise tabulation of machining parameters for each of the different types of operations. However, Table 5.31 is a compilation of typical factors for many common machining operations, (Ref. 5.9). Grinding typically uses a wheel speed of 6000ft/minute. The down feed will produce a rough finish if it is kept to about 0.001 inch per pass. A fine finish will be produced if the down-feed is kept to a maximum of 0.0005 inch per pass. The crossfeed is approximately one-third of the wheel width. The wheel type is A46KV with a water-base emulsion or chemical solution for the grinding fluid.

5.32 Electro-Chemical and Chemical Machining.

5.321 General Remarks. Electro-chemical and chemical machining have many potential advantages over conventional machining methods. These techniques are considered for the machining of complex shaped parts where conventional machining techniques may prove to be too difficult or expensive.

5.322 Electro-chemical milling. Electro-chemical machining for metal shaping subjects the chemically erodible workpiece to the action of anodic current flow in a suitable electrolyte. A second electrode, which is the tool, is provided for the cathodic action. The basic principles are the same as those generalized in Faraday's Law of Electrolysis. However, the electro-chemical machining, or ECM, process is the reverse of electrodeposition or electroplating. An exception is that the cathodic process involves the evolution of hydrogen in most cases, rather than the electrodeposition of a metal. There are a number of tool workpiece configurations that may be employed in the ECM process depending upon the particular type of metal removal geometry desired. It is normally required that fresh electrolyte is supplied to the workpiece. Alloy 6061 is essentially pure aluminum as far as the rate of the electro-chemical process is concerned. Hence from the Faraday Laws it is rather easily shown that 1.26 cubic-inches of the metal can be removed per minute at 100,000 amperes (assuming 100% efficiency). In practice, efficiencies of 80 to 90% are encountered. An electrolyte of 5 to 10 percent NaCl solution has been found to yield excellent results and the process can be carried out using voltages of 10-15 volts. The milling rate of the ECM process depends upon the current capacity of the power supply and the ability of the electrolyte system to provide fresh electrolyte. High electrolyte pressure requirements of 100-250 psi provide even electrolyte flow and satisfactory cutting conditions. Temperatures of about 120F produce good quality finishes.

5.323 Chemical milling. The removal of metal stock by chemical dissolution or "chem-milling" in general has also many potential advantages over conventional milling methods. The removal of metal by dissolving in an alkaline or acid solution is now routine for specialized operations on aluminum, (Ref. 5.6). For flat parts on which large areas having complex or wavy peripheral outlines are to be reduced only slightly in thickness, chemical milling is usually the most economical method. It is basically a three-step process, (Ref. 5.10). A maskant is applied to protect surface areas that will not be milled. The metal is immersed in an etching bath which may be acidic or basic to remove metal from specific areas so as to produce the desired configuration. Finally the maskant is stripped from the part. To produce a simple shape, the masking and milling procedure is only performed once. Complex designs are usually produced by repeating the masking and milling sequence until the desired shape is achieved.

Standard mechanical property tests indicate that chemical milling has no appreciable effect on the compression, tension or shear properties of aluminum alloy 6061, (Ref. 5.11, Fatigue tests of 6061-T4 show that chemical milling does not significantly affect the fatigue life of the alloy. The alloy 6061 can be milled in all forms and in the O, T4, T6 or T62 Conditions.

RELATIVE FORMABILITY OF HEAT-TREATABLE ALLOYS
IN ORDER OF DECREASING FORMABILITY

TABLE 5.21

Source	(Ref. 5.2) Order of Decreasing Formability
	No. 21 and No. 22 Brazing Sheet
	6061
	6066
	2024
	2014
	7075
	7178

why are alloys listed here not same as shown in fig 5.232 p 45

APPROXIMATE BEND RADII FOR 90 DEGREE COLD BEND (a)

TABLE 5.211

Source	(Ref. 5.1)							
Temper	Thickness, t, inches							
	1/64	1/32	1/16	1/8	3/16	1/4	3/8	1/2
O	0	0	0	0	0-1t	0-1t	½t-2t	1t-2½t
T4 (b)	0-1t	0-1t	½t-1½t	1t-2t	1½t-3t	2t-4t	2½t-4t	3t-5t
T6 (b)	0-1t	½t-1½t	1t-2t	1½t-3t	2t-4t	3t-4t	3½t-5½t	4t-6t

(a) Radii for various thickness expressed in terms of thickness, t

(b) Alclad sheet can be bent over slightly smaller radii than the corresponding tempers of the uncoated alloy

RECOMMENDED MAXIMUM HOLDING TIMES FOR 6061-T6 ALLOY PRIOR TO FORMING, AS A FUNCTION OF HOLDING TEMPERATURE

TABLE 5.212

Source	(Ref. 5.4)
Temperature of Hold, F	Time in Indicated Units
300	100-200 hours
325	50-100 hours
350	8-10 hours
375	1-2 hours
400	30 minutes
425	15 minutes
450	5 minutes
500	No

Note: The above guide indicates maximum heating periods; it should be understood that in many instances, shorter heating times will give satisfactory results.

RELATIVE FORMABILITY OF HEAT-TREATABLE ALLOYS FOR EXTRUSIONS AND TUBES IN ORDER OF DECREASING FORMABILITY

TABLE 5.22

Source	(Ref. 5.2)
Extrusions	Tubes
6063, 6463	6063
6061, 6062	6061, 6062
2024	2024
2014	2014
7075, 7079	7075
7178	

HEAT-TREAT TEMPERS FOR HAND FORGINGS

TABLE 5.231

Source	(Ref. 5.8)
Temper	Treatment
F	As forged, no thermal treatment following fabrication operation
W	Solution heat-treated and quenched in water at 140F
T4	Solution heat-treated, quenched in water at 140F and naturally aged to a substantially stable condition
T41	Solution heat-treated, quenched in water at 212F and naturally aged to a substantially stable condition
T6	Solution heat-treated, quenched in water at 140F and artificially aged
T62	Solution heat-treated, quenched in water at 140F, stress relieved by cold compression, artificially aged

MACHINING RECOMMENDATIONS FOR SOLUTION TREATED AND AGED 6061 ALLOY

TABLE 5.31

Source	Ref. 5.7						
		High Speed Tool			Carbide Tool		
Operation	Cutting Conditions*	Speed fpm	Feed ipr	Tool mat'l	Speed fpm	Feed ipr	Tool mat'l
Single point Turning	0.250 inch depth of cut	600	0.015	T1, M1	1100	0.015	C-1
	0.050 inch depth of cut	800	0.008	T1, M1	1400	0.008	C-2
Form tool, turning	0.500 inch form tool width	450	0.0035	T1, M1,	1000	0.0035	C-2
	0.750 inch form tool width	450	0.0035	HSS	1000	0.0035	C-2
	1.000 inch form tool width	450	0.003	HSS	1000	0.003	C-2
	1.500 inch form tool width	450	0.0025	HSS	1000	0.002	C-2
	2.000 inch form tool width	450	0.002	HSS	1000	0.002	C-2
Boring	0.010 inch depth of cut	600	0.008	T1, M1,	1100	0.010	C-1, C-3
	0.050 inch depth of cut	570	0.010	HSS	1050	0.015	C-1, C-3
	0.100 inch depth of cut	540	0.015	HSS	1000	0.020	C-1, C-3
Planing	0.500 inch depth of cut	300	0.060	T1, M1	300	0.060*	C-2
	0.050 inch depth of cut	300	0.050	T1, M1	300	0.050	C-2
	0.010 inch depth of cut	300	3/4**	T1, M1	300	3/4**	C-2
Face milling	0.250 inch depth of cut	800	0.020*	T1, M1	max	0.018*	C-2
	0.050 inch depth of cut	1000	0.022*	T1, M1	max	0.020*	C-2
End milling (Profiling)	3/4 inch cutter diameter	700	0.006*	M1, M10	1200	0.005*	C-2
	1/2 inch cutter diameter	700	0.009*	M1, M10	1200	0.008*	C-2
	1/8 inch cutter diameter	1000	0.0007*	M1, M10	1800	0.0005*	C-2
	3/8 inch cutter diameter	1000	0.005*	M1, M10	1800	0.004*	C-2
	3/4 inch cutter diameter	1000	0.007*	M1, M10	1800	0.006*	C-2
	1 to 2 inch cutter diameter	1000	0.010*	M1, M10	1800	0.009*	C-2
Drilling	1/8 inch nominal hole diameter	250	0.003	M1, M10			
	1/4 inch nominal hole diameter	250	0.007	HSS			
	1/2 inch nominal hole diameter	250	0.012	HSS			
	3/4 inch nominal hole diameter	250	0.016	HSS			
	1 inch nominal hole diameter	250	0.020	HSS			
	1 1/2 inch nominal hole diameter	250	0.025	HSS			
	2 inch nominal hole diameter	250	0.030	HSS			
	3 inch nominal hole diameter	250	0.030	HSS			

* Feed - inches per tooth

** Feed - 3/4 the width of square nose finishing tool

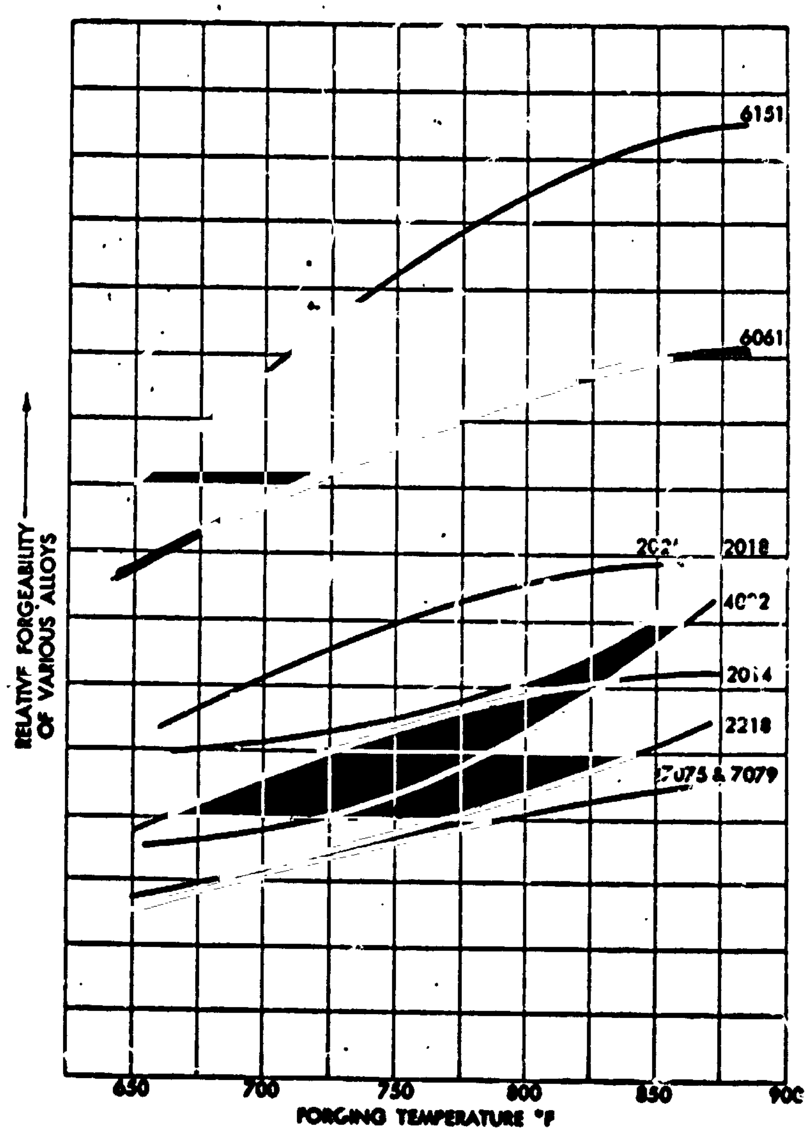

FIG. 5.232 RELATIVE FORGEABILITY OF VARIOUS ALUMINUM ALLOYS

(Ref. 5.8, p. 264)

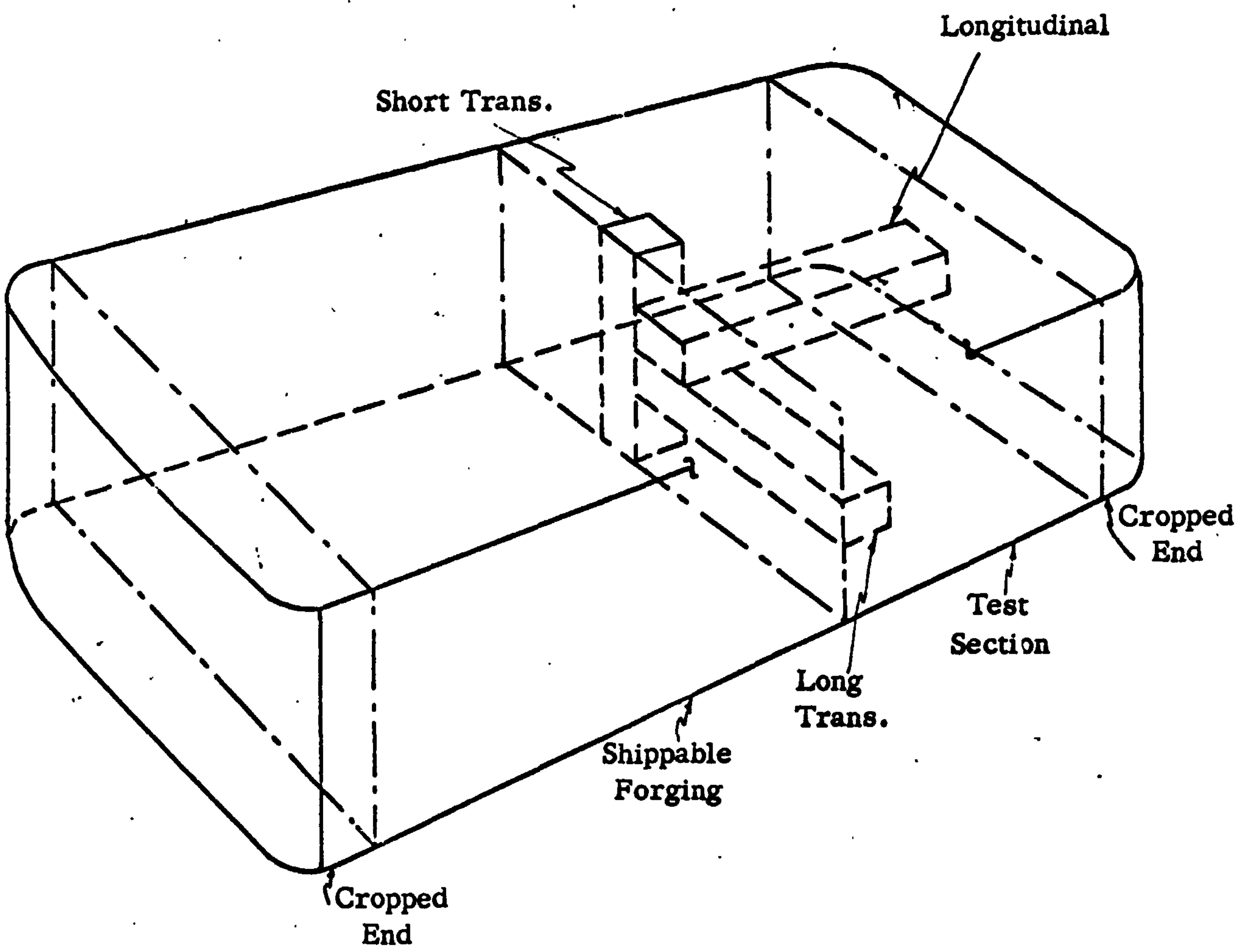

FIG. 5.233 LOCATIONS OF TEST BARS FOR TESTING HAND FORGINGS OF RECTANGULAR OR SQUARE CROSS SECTIONS

(Ref. 5.8, p. 59)

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CHAPTER 6

SPACE ENVIRONMENT EFFECTS

6.1 General. Aluminum alloys have been used in both structural and non-structural applications in launch vehicles and spacecraft with excellent success since, in general, the aluminum alloys are relatively insensitive to degradation in the typical space environmental conditions. The vapor pressures of the structural aluminum alloys are sufficiently high, (Fig. 6.1) so that the combined temperature-vacuum effects generally are negligible. Structural alloys such as 6061 are sufficiently hardened so that nuclear and space indigenous radiation induced defects do not significantly affect mechanical and physical properties, at room ambient and elevated temperatures, below accumulated doses of about 10^{22} particles/cm^2. When irradiated at cryogenic temperatures, the threshold may be lowered one or two decades, but the probabilities of experiencing doses on this order of magnitude are extremely remote except in the vicinity of nuclear reactors.

Elevated temperatures, hard vacuums, high energy radiations, and micrometeoroids can singularly and collectively influence surface characteristics of 6061 by desorption processes and erosion. These phenomena might be of great importance if optical properties, lubrication, certain electrical properties, etc., were critical design parameters.

Sputtering of the surface by atomic or molecular particles can deteriorate surface finishes in a relatively short period. A 300 Å coating of aluminum (10^{-5} gm/cm^2) can be destroyed in one month during a period of low intensity solar wind or in several hours during a solar storm, for example. Threshold energies for sputtering reactions are quite low, in the order of 6, 11, and 12 ev for O, N_2 and O_2 particles, respectively. Estimates and surface erosion by sputtering are given in Tables 6.1 and 6.2 for aluminum alloys.

Micrometeoroids can produce surface erosion similar to sputtering, although perhaps on a more macroscopic scale, as well as punctures. Micrometeoroids vary widely in mass, composition, velocity, and flux; generalizations about the rates of erosion and penetration, therefore, must be used with care. The predicted frequency of impact as a function of meteoroid mass is given in Fig. 6.2. Data are given in Figs. 6.3 and 6.4 on the penetration and cratering of aluminum alloy skins of various thicknesses.

The surface erosion of 6061 due to corpuscular radiation is probably insignificant, amounting to something on the order of 10 μ per year. Indigenous space radiation, however, will tend to accelerate the removal of surface films on the 6061. The removal of such films might result in loss of lubricity and an increased propensity to "cold weld". The interaction of indigenous radiation with desorption gases might cause some spurious, transient electrical conditions when 6061 is used for electrical applications. The interaction of indigenous radiation with the 6061 will produce some internal heating that might be significant for small items and some induced radioactivity.

IMPACT FLUX, MASS FLUX, PARTICLE CONCENTRATION, AND DENSITY FOR THE PARTICLE BELT SURROUNDING THE EARTH

TABLE 6.1

Source		Ref. 6.3			
Zone	Altitude[(a)]	Flux Impact (m^{-2} - sec^{-1})	Flux Mass (gm-cm^{-2}-sec^{-1})	Particle Concentration (cm^{-3})	Density (gm-cm^{-3})
1	100km < h < 400km	10^{-1} to 10^{0}	10^{-13} to 10^{-12}	4×10^{-11} to 4×10^{-10}	4×10^{-19} to 4×10^{-18}
2	400km < h < $2R_E$	10^{-4} to 10^{-2}	10^{-16} to 10^{-14}	4×10^{-14} to 4×10^{-12}	4×10^{-22} to 4×10^{-20}
3	h > $2R_E$	5×10^{-6} to 10^{-4}	5×10^{-18} to 10^{-16}	2×10^{-15} to 4×10^{-14}	2×10^{-23} to 4×10^{-22}
	Zodiacal cloud	2×10^{-6} to 1.2×10^{-3}	10^{-17} to 10^{-15}	10^{-15} to 10^{-13}	3×10^{-23} to 3×10^{-21}

(a) h is distance from earth's surface in km unless given in R_E (earth radii).

ESTIMATED RATE OF REMOVAL AND TIME TO REMOVE 1 Å OF ALUMINUM BY SPUTTERING

TABLE 6.2

Source	Ref. 6.2			
	Orbiting Vehicle		Escaping Vehicle	
Height (Km)	Rate (atom cm^{-2} sec^{-1})	Time (sec/Å)	Rate (atom cm^{-2} sec^{-1})	Time (sec/Å)
100	3.1×10^{16}	1.9×10^{-2}	3.4×10^{17}	1.8×10^{-3}
220	2.0×10^{13}	30	2.0×10^{17}	3.0×10^{-3}
700	2.2×10^{9}	2.7×10^{5}	3.4×10^{11}	1.8×10^{3}
2500	4.3×10^{5}	1.4×10^{9}	1.6×10^{8}	3.8×10^{6}

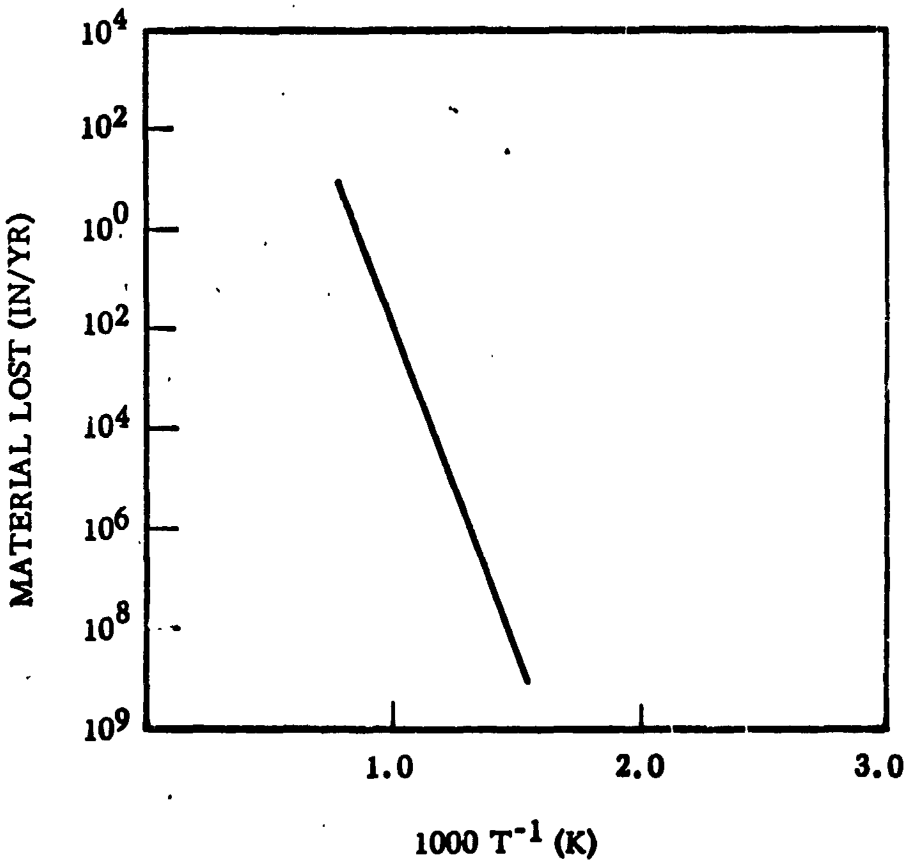

FIG. 6.1 EVAPORATION RATE FOR ALUMINUM (Ref. 6.1)

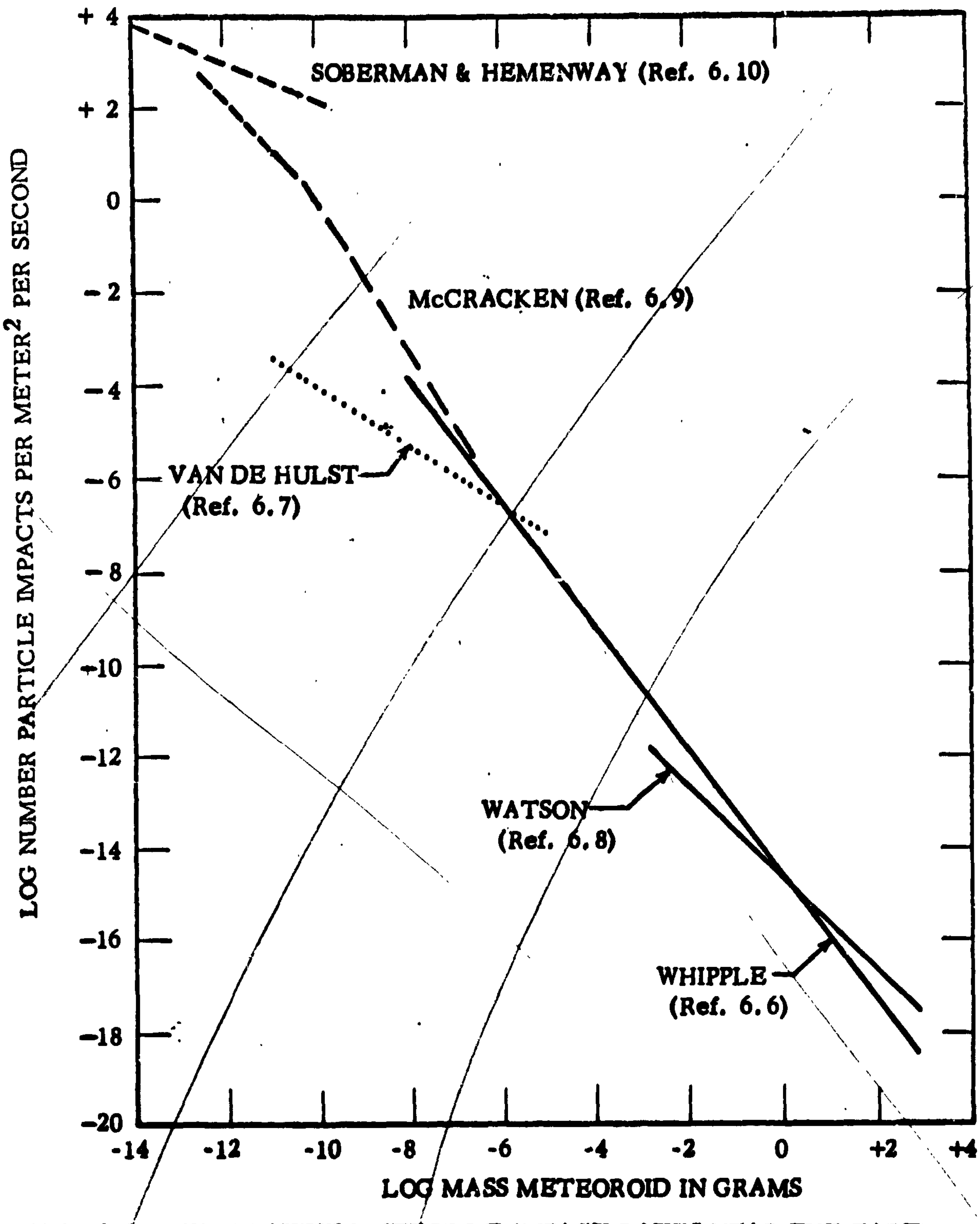

FIG. 6.2 . CUMULATIVE METEOROID IMPACT RATES NEAR THE EARTH (Ref. 6.1)

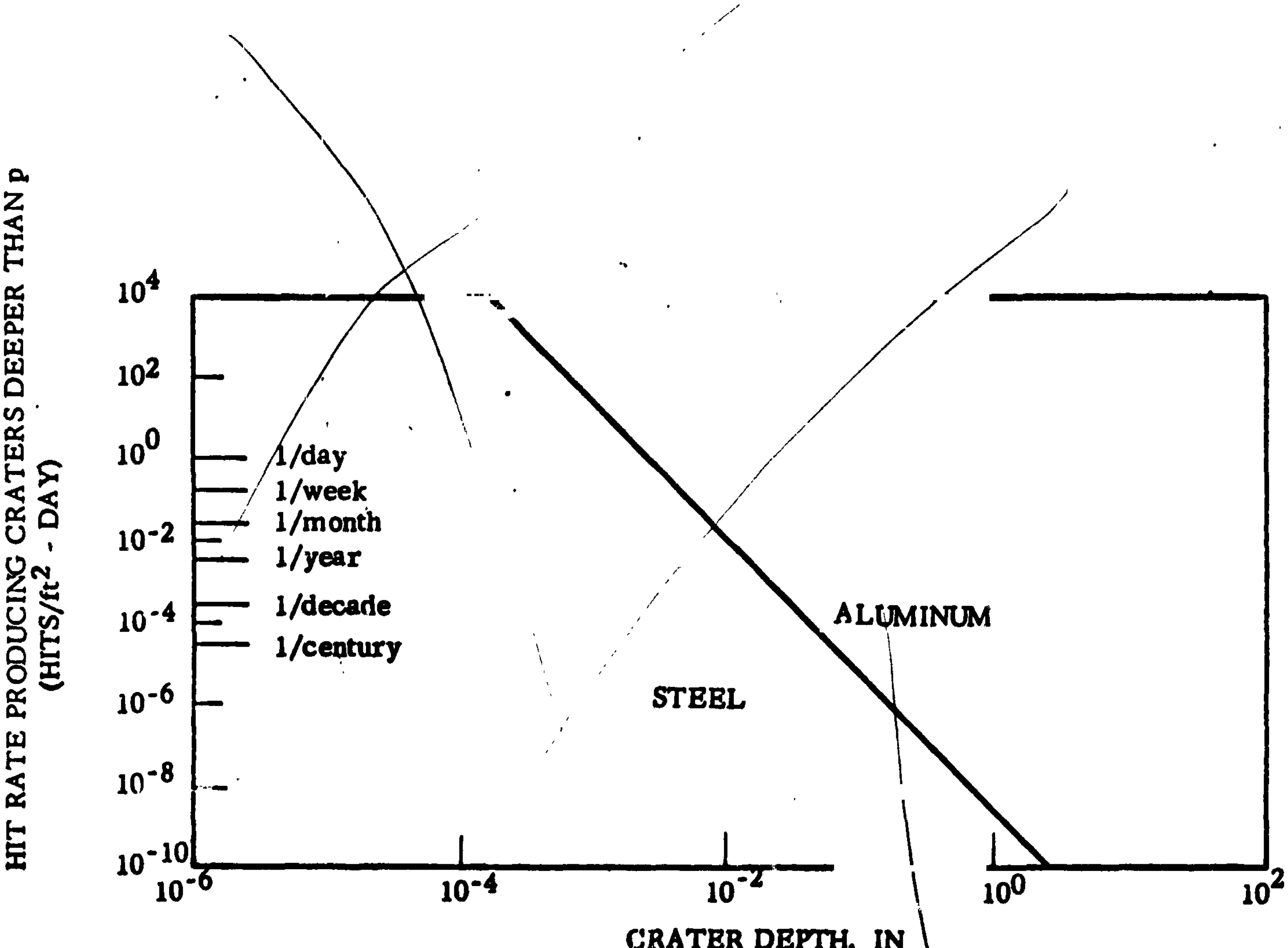

FIG. 6.3 HIT RATE vs CRATER DEPTH IN THE EARTH NEIGHBORHOOD BUT WITHOUT EARTH SHIELDING

(Ref. 6.4)

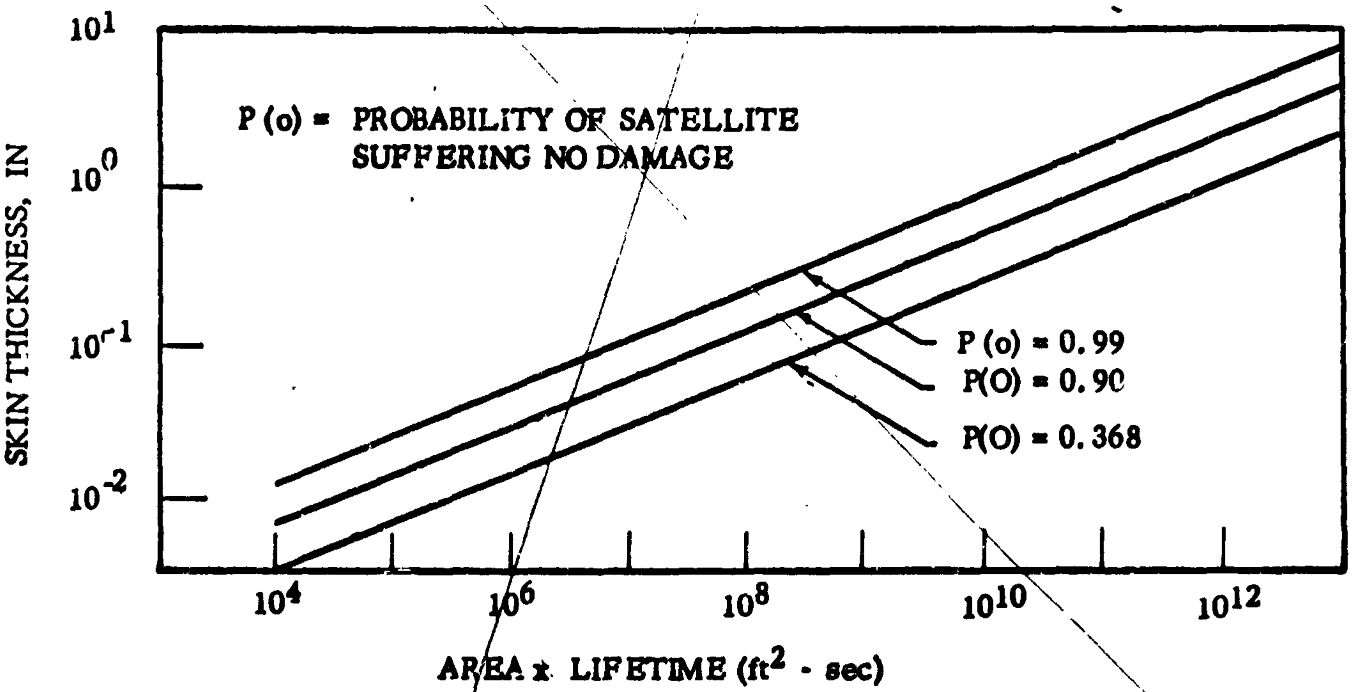

FIG. 6.4 ALUMINUM SKIN THICKNESS REQUIRED FOR METEOROID PROTECTION (Ref. 6.5)

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CHAPTER 7

STATIC MECHANICAL PROPERTIES

7.1 Specified Properties

7.11 — NASA Specified Properties.

7.111 NASA specified mechanical properties for die forgings and separately forged test bars, Table 7.111.

7.112 NASA specified mechanical properties for hand forgings, Table 7.112.

7.12 — AMS Specified Properties

7.121 AMS specified properties are given in detail in Ref. 7.1.

7.13 — Military Specified Properties

7.14 — Federal Specified Properties

7.15 — ASTM Specified Properties

7.151 ASTM specified properties are given in the 1965 ASTM Book of Standards, Part 6, (Ref. 7.2).

7.16 Aluminum Association Mechanical Property Limits

7.161 Aluminum Association mechanical property limits are given in the Aluminum Association, "Standards for Aluminum Mill Products", (Ref. 7.3).

7.2 Elastic Properties and Moduli

7.21 Poisson's ratio. 0.33, (Ref. 7.8).

7.22 Young's modulus of elasticity, E.

7.221 Design value of E. $E = 9.9 \times 10^3$ ksi, (Ref. 7.4).

7.222 Typical value of E. $E = 10.0 \times 10^3$ ksi, (Ref. 7.5).

7.223 Effect of temperature on the tensile and compressive moduli (E and E_c), Fig. 7.223.

7.224 Modulus of elasticity at low temperatures, Fig. 7.224.

7.23 Compression modulus E_c, (See also Fig. 7.223).

7.231 Design value of E_c. $E_c = 10.1 \times 10^3$ ksi, (Ref. 7.4).

7.24 Modulus of rigidity (shear modulus), G.

7.241 Design value of G. $G = 3.8 \times 10^3$ ksi, (Ref. 7.4).

7.25 Tangent modulus

7.251 Tangent modulus curves for sheet and plate in T6 Condition, Fig. 7.251.

7.252 Tangent modulus curve (compression) for extrusion in T6 Condition, Fig. 7.252.

7.26 Secant modulus

7.27 Bending modulus of rupture for round tubing, Fig. 7.27.

7.28 Torsional modulus of rupture for tube in T6 Condition, Fig. 7.28.

7.3 Hardness

7.31	Brinell scale (500 kg load)	Condition O	30
		T4, T451	65
		T6, T651	95, (Ref. 7.6).

7.32 End-quench hardenability of alloy in solution treated and aged condition, Fig. 7.32.

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7.4 Strength Properties

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7.4111 Design properties for sheet, plate, extrusions, rolled bar, rod and shapes and drawn tube and pipe, Table 7.4111.

7.4112 Design properties for die forging and hand forgings, Table 7.4112.

7.4113 Elongation values for sheet, plate and tube, Table 7.4113.

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7.4123 Stress-strain diagram for 0.100 inch sheet (T) at room and low temperatures, Fig. 7.4123.

7.4124 Stress-strain curves for alloy in T6 Condition, Fig. 7.4124.

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7.4132 Effect of temperature on tensile yield strength (all products) of alloy in T6 Condition, Fig. 7.4132.

7.4133 Effect of exposure and test temperature on tensile properties of alloy in T6 Condition, Fig. 7.4133.

7.4134 Effect of exposure and test temperature on tensile properties of alloy in Condition O, Fig. 7.4134.

7.4135 Effect of cryogenic temperatures on tensile properties of T6 sheet and forgings, Fig. 7.4135.

7.4136 Effect of cryogenic temperatures on tensile elongation and reduction of area, Fig. 7.4136.

7.42 Compression

7.421 Design compression properties

7.4211 Design compression properties for sheet, plate, extrusions, rolled drawn or cold finished products, drawn tube and pipe, see Table 7.4111.

7.4212 Design compression properties for die forgings and hand forgings, see Table 7.4112.

7.422 Stress-strain diagrams (compression)

7.4221 Typical stress-strain curves in compression for sheet, plate and extrusions in T6 Condition, see Fig. 7.4121.

7.4222 Typical compressive stress-strain curves for T6 clad sheet at 200, 300, 400 and 500F, Fig. 7.4222.

7.43 Bending

7.44 Shear and torsion

7.441 Design shear properties

7.4411 Design shear properties for various products in various conditions, see Table 7.4111.

7.4412 Design shear properties for die forgings and hand forgings, see Table 7.4112.

7.4413 Effect of low temperature on shear strength of sheet in T6 Condition, Fig. 7.4413.

7.45 Bearing

7.451 Design bearing properties

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7.4513 Allowable column and crushing stresses for tubing, Fig. 7.4513.

7.46 Fracture

7.461 Notch strength

7.4611 Effect of test temperature on smooth and notched tensile properties of 6061 sheet in T6 Condition, Fig. 7.4611.

7.4612 Effect of cryogenic temperatures on notch strength ratio of T6 sheet, Fig. 7.4612.

7.462 Fracture toughness

NASA SPECIFIED MECHANICAL PROPERTIES FOR DIE FORGINGS AND SEPARATELY FORGED TEST BARS

TABLE 7.111

Alloy	6061-T6 (b)	
Specification	NASA-MSFC-SPEC-144B	
Product	Die Forgings and Separately Forged Test Bars	
Max. sect. thick, in	4	
Orientation	A	B
F_{tu}, -min-ksi (a)	38.0	38.0
F_{ty}, -min-ksi (a)	35.0	35.0
e(2 in or 4D), -min-percent	7	5

A Test specimen parallel to forging flow lines

B Test specimen not parallel to forging flow lines

(a) Tensile and yield strength test requirements may be waived for material in any direction in which the dimension is less than 2 inches because of the difficulty in obtaining a tension test specimen suitable for routine control testing.

(b) Die forgings in some configurations of this alloy can be purchased in the heat treated and mechanically stress relieved T652 temper conforming to the mechanical properties requirements specified for the T6 temper.

NASA SPECIFIED MECHANICAL PROPERTIES FOR HAND FORGINGS

TABLE 7.112

Alloy	6061-T6			
Specification	NASA-MSFC-SPEC-144B			
Product	Hand Forgings (a)			
Thickness, in (b)	Axis of Test Specimen	F_{tu}, ksi (min) (c)	F_{ty}, ksi (min) (c)	e(in 2 in or 4D) percent (min)
≤ 4.000	L	38.0	35.0	10
	LT	38.0	35.0	8
	ST	37.0	33.0	5
4.001 - 8.000	L	37.0	34.0	8
	LT	37.0	34.0	6
	ST	35.0	32.0	4

(a) Maximum cross-sectional area is 256 square inches.
(b) Thickness is measured in the short transverse direction and applies to the dimension "as forged", before machining.
(c) Tensile property requirements may be waived for directions in which the dimension is less than 2 inches.

in Table on p 63
WHY refer to as NASA Specs?

DESIGN PROPERTIES FOR SHEET, PLATE, EXTRUSIONS, ROLLED BAR, ROD AND SHAPES, TUBE, PIPE

TABLE 7.4111

Alloy	6061								6061 and 6062		6061		6061 and 6062			
Form	Sheet and plate								Extruded bar, rod and shapes		Bar, rod, wire and shapes; rolled, drawn or cold-finished		Tube, drawn		Pipe	
Condition	Heat treated —T4 or —T451				Heat treated and aged —T6 or —T651				Heat treated —T4, —T4510, —T4511	Heat treated and aged —T6, —T6510, —T6511	Heat treated —T4 or —T451	Heat treated and aged —T6 or —T651	Heat treated —T4	Heat treated and aged —T6	Heat treated and aged —T6	
Thickness, in	0.010–2.000		2.001–3.000		0.010–2.000		2.001–3.000		≲3(c)	≲3(c)	≲8.000 (d)	≲8.000 (d)	0.025–0.500	0.025–0.500	0.049–0.154	0.065–0.687
Size, in															½-¾	1-12
Basis	A	B	A	B	A	B	A	B	A	A	A	A	A	A	A	A
Mechanical properties:																
F_{tu}, ksi:																
L	...	...	...	...	42	43	...	...	26	38	30	42	30	42	42	38
LT	30	32	30	32	42	43	42	43	...	36	...	...	...	...		...
F_{ty}, ksi:																
L	...	...	...	...	36	38	...	...	16	35	16	35	16	35	35	35
LT	16	18	16	18	35	37	35	37	...	33	...	...	...	...	...	...
F_{cy}, ksi:																
L	...	...	...	...	35	37	...	...	14	34	14	34	14	34	34	34
LT	16	18	...	...	36	38	...	...	...	35	...	...	...	...	...	...
F_{su}, ksi	20	21	...	...	27	28	...	...	16	24	20	27	20	27	27	24
F_{bru}, ksi:																
(e/D=1.5)	48	51	...	...	67	69	...	...	42	61	48	67	48	67	67	61
(e/D=2.0)	63	67	...	...	88	90	...	...	55	80	63	88	63	88	88	80
F_{bry}, ksi:																
(e/D=1.5)	22	25	...	...	50	53	...	...	22	49	22	49	22	49	49	49
(e/D=2.0)	26	29	...	...	58	61	...	...	26	56	26	56	26	56	56	56
e, percent:																
L	...	...	...	...	...	...	...	...	16	10	18	10	(a)	(a)	12	10
LT	(e)	...	16	...	(e)	...	6	...	...	...	...	...	...	...	...	...

(Ref. 7.4)

(a) Elongation values for these columns are given in Table 7.4113.

(c) Cross section area ≲ 32 square-inch.

(d) Cross section area ≲ 50 square-inch.

DESIGN PROPERTIES FOR DIE FORGINGS AND HAND FORGINGS

TABLE 7.4112

Alloy	6061		
Form	Die forgings	Hand forgings	
Condition	Heat treated and aged −T6 and −T652		
Thickness, in.	≤4	≤4	≥4, ≤8
Cross-sectional area, in.^{2}	....	≤144	≤256
Basis	A	A	A
Mechanical properties:			
F_{tu}, ksi:			
L	38	38	37
LT	38	38	37
ST	....	37	35
F_{ty}, ksi:			
L	35	35	34
LT	35	35	34
ST	....	33	32
F_{cy}, ksi:			
L	36	36	35
LT	36	36	35
ST	....	34	33
F_{su}, ksi	25	25	24
F_{bru}, ksi:			
(e/D=1.5)	61	61	59
(e/D=2.0)	76	76	74
F_{bry}, ksi:			
(e/D=1.5)	54	54	53
(e/D=2.0)	61	61	59
e, percent:			
L	7	10	8
LT	5	8	6
ST	....	5	4

(Ref. 7.4)

ELONGATION VALUES FOR SHEET, PLATE AND TUBE

TABLE 7.4113

Condition in table 3.2.6.0(b)	Thickness range, inch	Elongation, percent	
-T4 or -T451 (6061 sheet and plate)..	0.010-0.020	14	
	0.021-0.249	16	
	0.250-1.000	18	
	1.001-2.000	16	
-T6 or -T651 (6061 sheet and plate)..	0.010-0.020	8	
	0.021-0.499	10	
	0.500-1.000	9	
	1.001-2.000	8	
		Full-section specimen	Cut-out specimen
-T4 (6061 and 6062 tube)...........	0.025-0.049	16	14
	0.050-0.259	18	16
	0.260-0.500	20	18
-T6 (6061 and 6062 tube)...........	0.025-0.049	10	8
	0.050-0.259	12	10
	0.260-0.500	14	12

(Ref. 7.4)

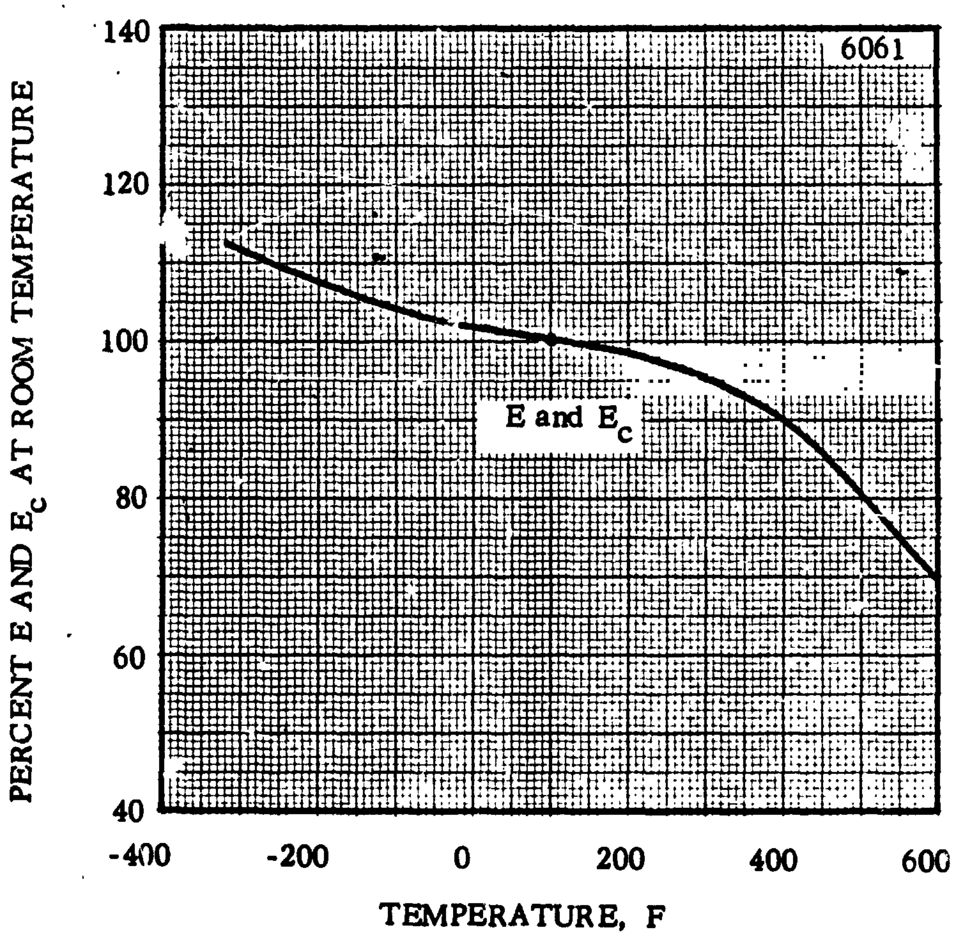


FIG. 7.223 EFFECT OF TEMPERATURE ON THE TENSILE AND COMPRESSIVE MODULI (E AND E_c)

(Ref. 7.4)

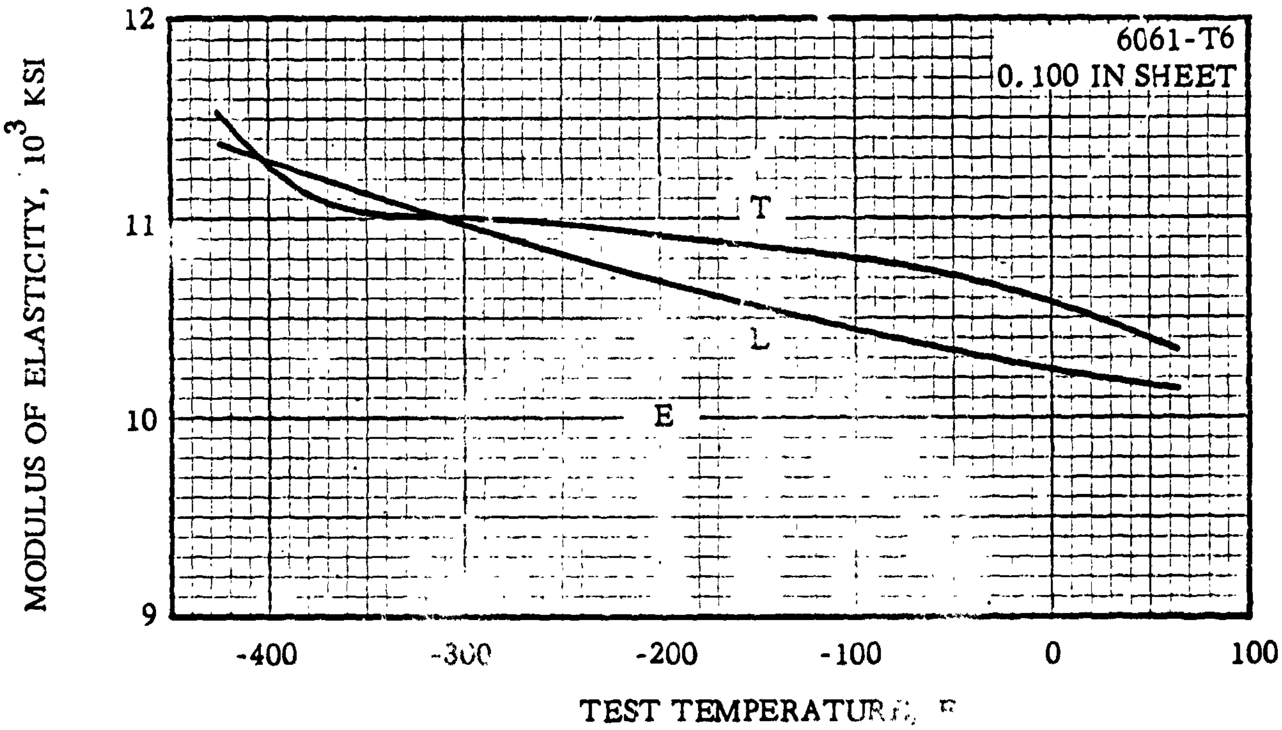


FIG. 7.224 MODULUS OF ELASTICITY AT LOW TEMPERATURES

(Ref. 7.9)

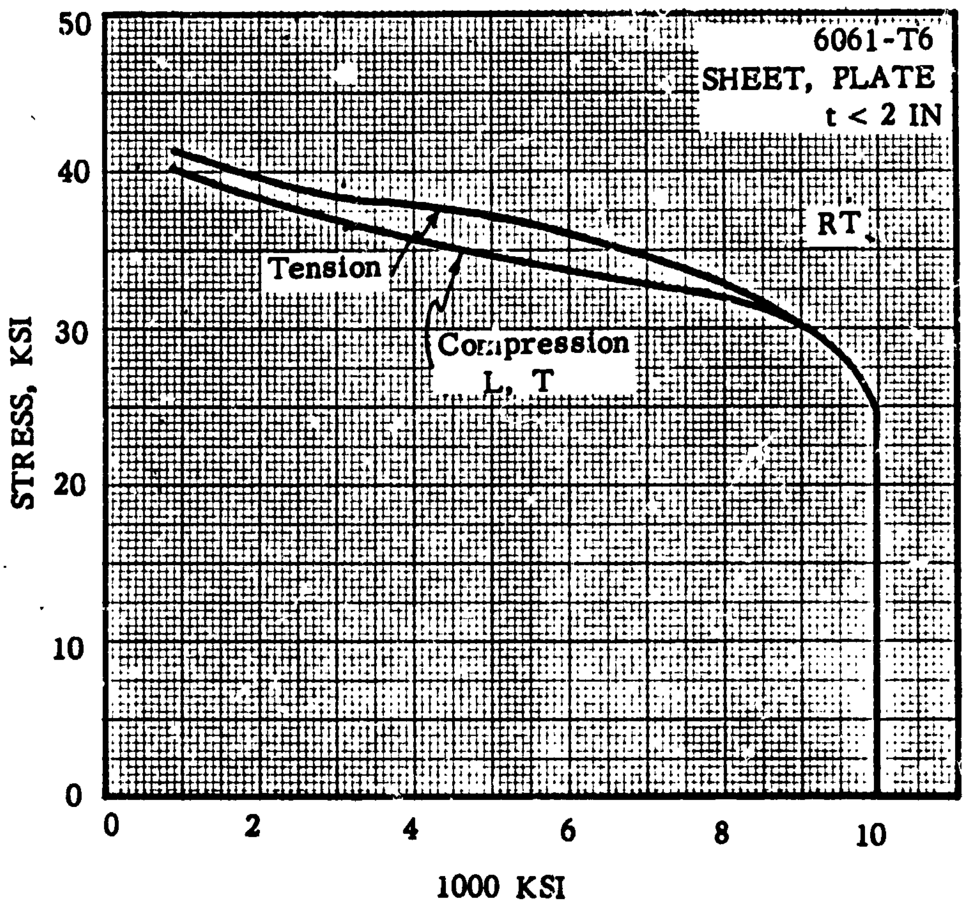


FIG. 7.251 TANGENT MODULUS CURVES FOR 6061 SHEET AND PLATE IN T6 CONDITION

(Ref. 7.4)

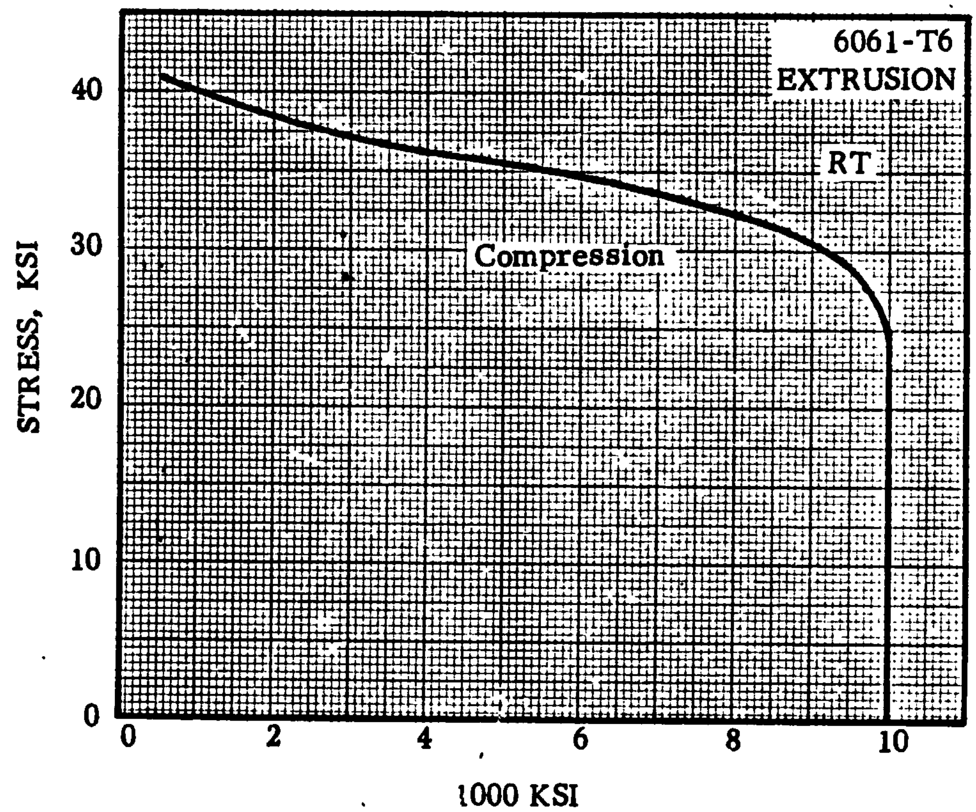


FIG. 7.252 TANGENT MODULUS CURVE FOR 6061 EXTRUSION T6 CONDITION

(Ref. 7.4)

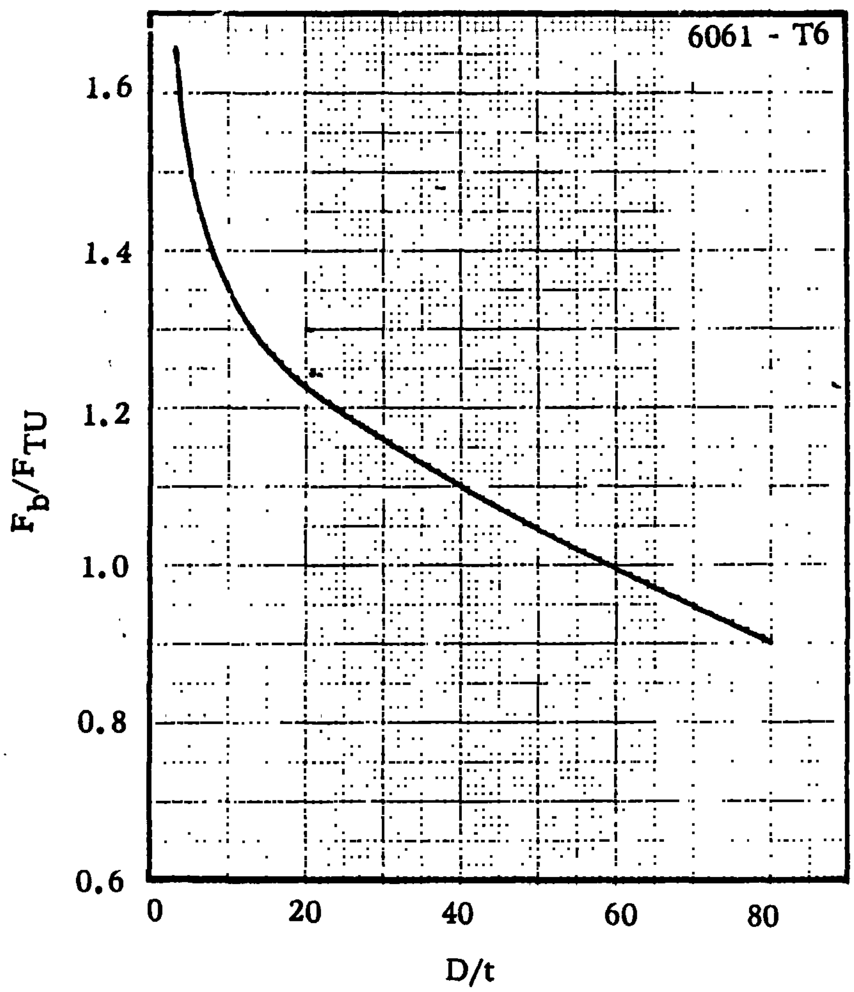


FIG. 7.27 BENDING MODULUS OF RUPTURE FOR ALUMINUM 6061-T6 ROUND TUBING

(Ref. 7.4)

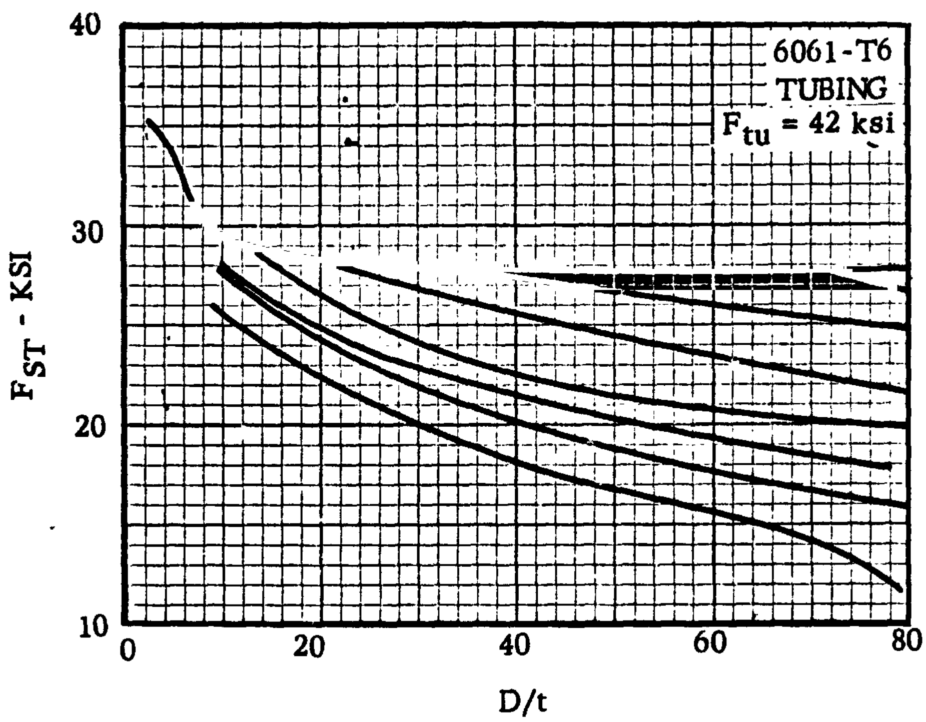


FIG. 7.28 TORSIONAL MODULUS OF RUPTURE FOR TUBE IN T6 CONDITION

(Ref. 7.4)

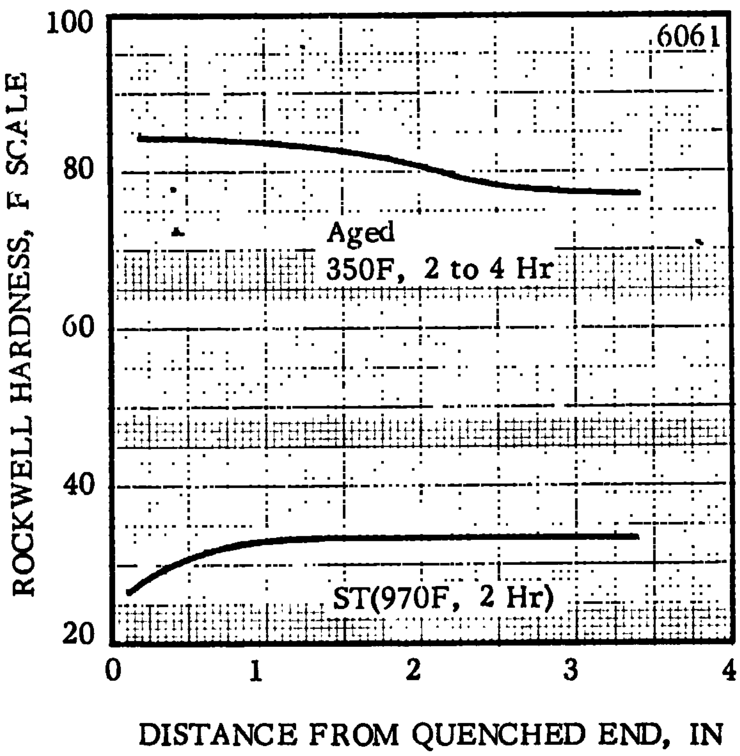


FIG. 7.32 END-QUENCH HARDENABILITY OF 6061 IN SOLUTION TREATED AND AGED CONDITION

(Ref. 7.7)

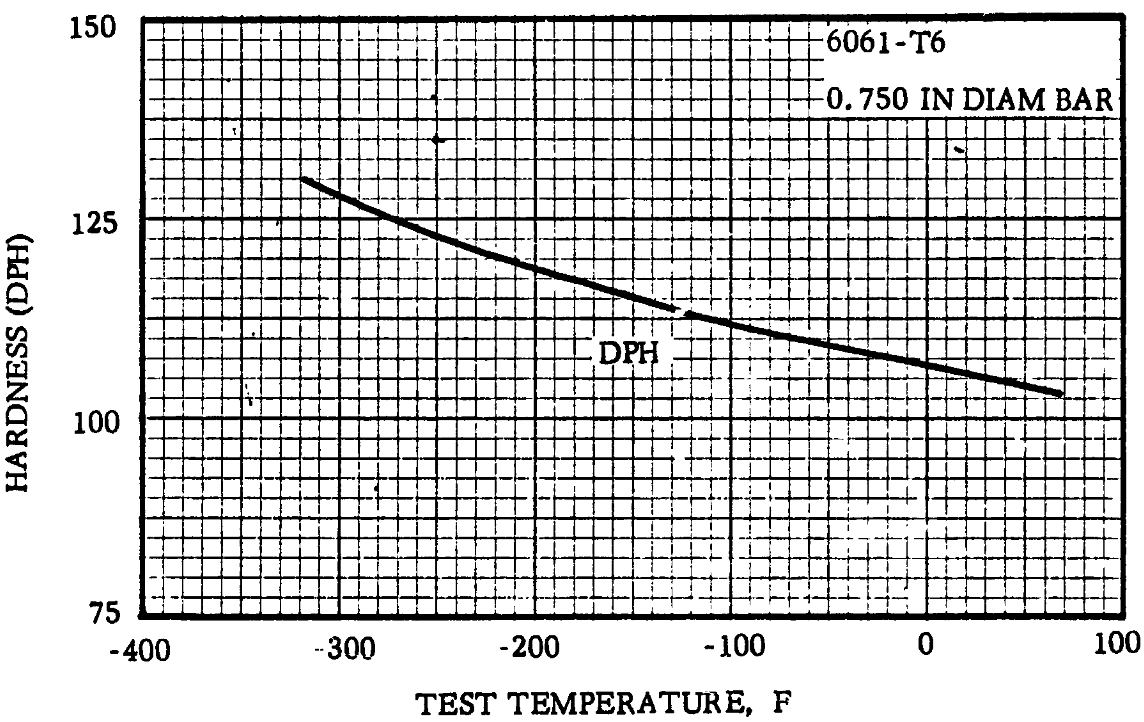


FIG. 7.33 HARDNESS OF T6 BAR AT CRYOGENIC TEMPERATURES (Refs. 7.17, 7.19, 7.20)

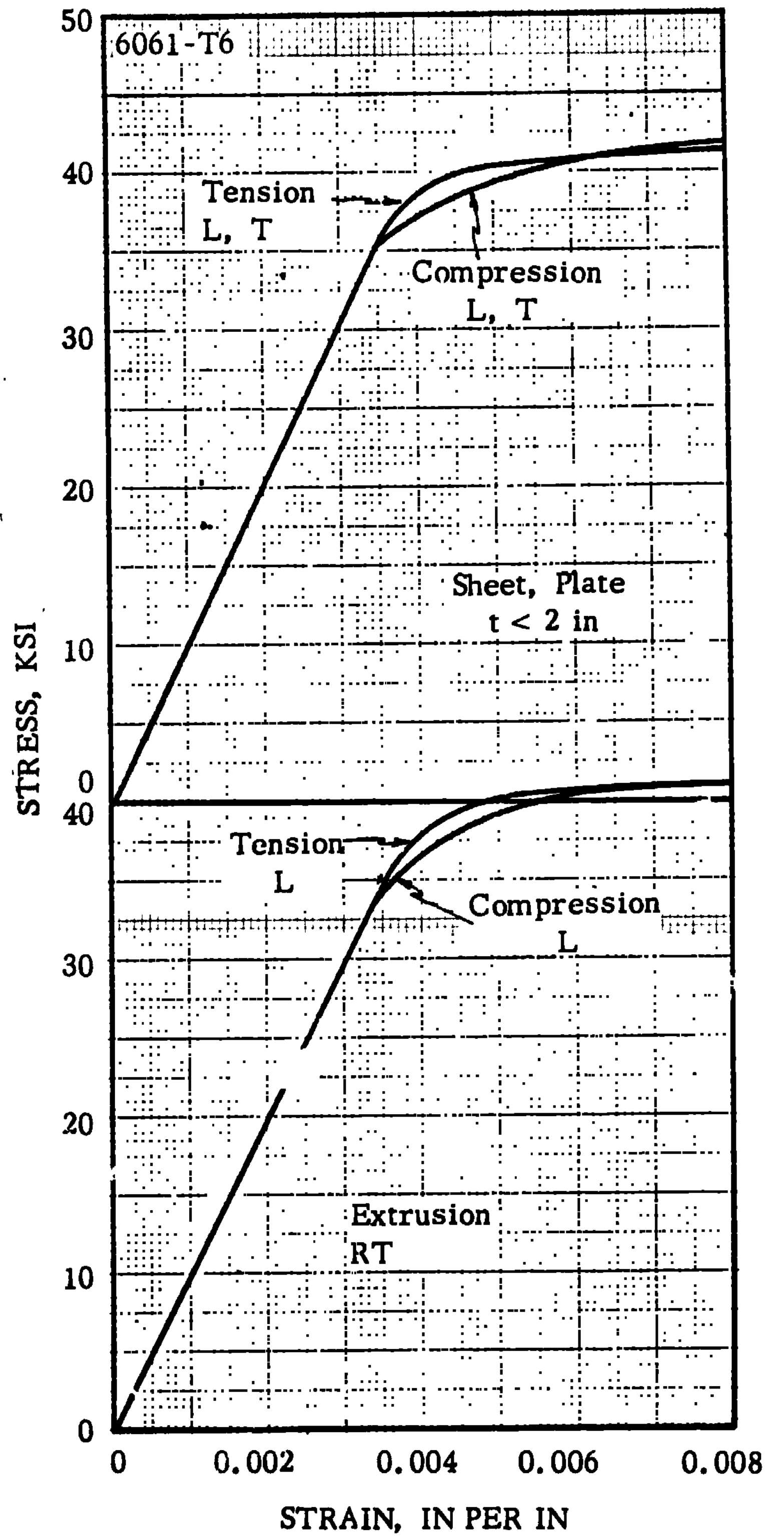


FIG. 7.4121 ROOM TEMPERATURE TENSION AND COMPRESSION STRESS-STRAIN CURVES FOR 6061 IN T6 CONDITION

(Ref. 7.4)

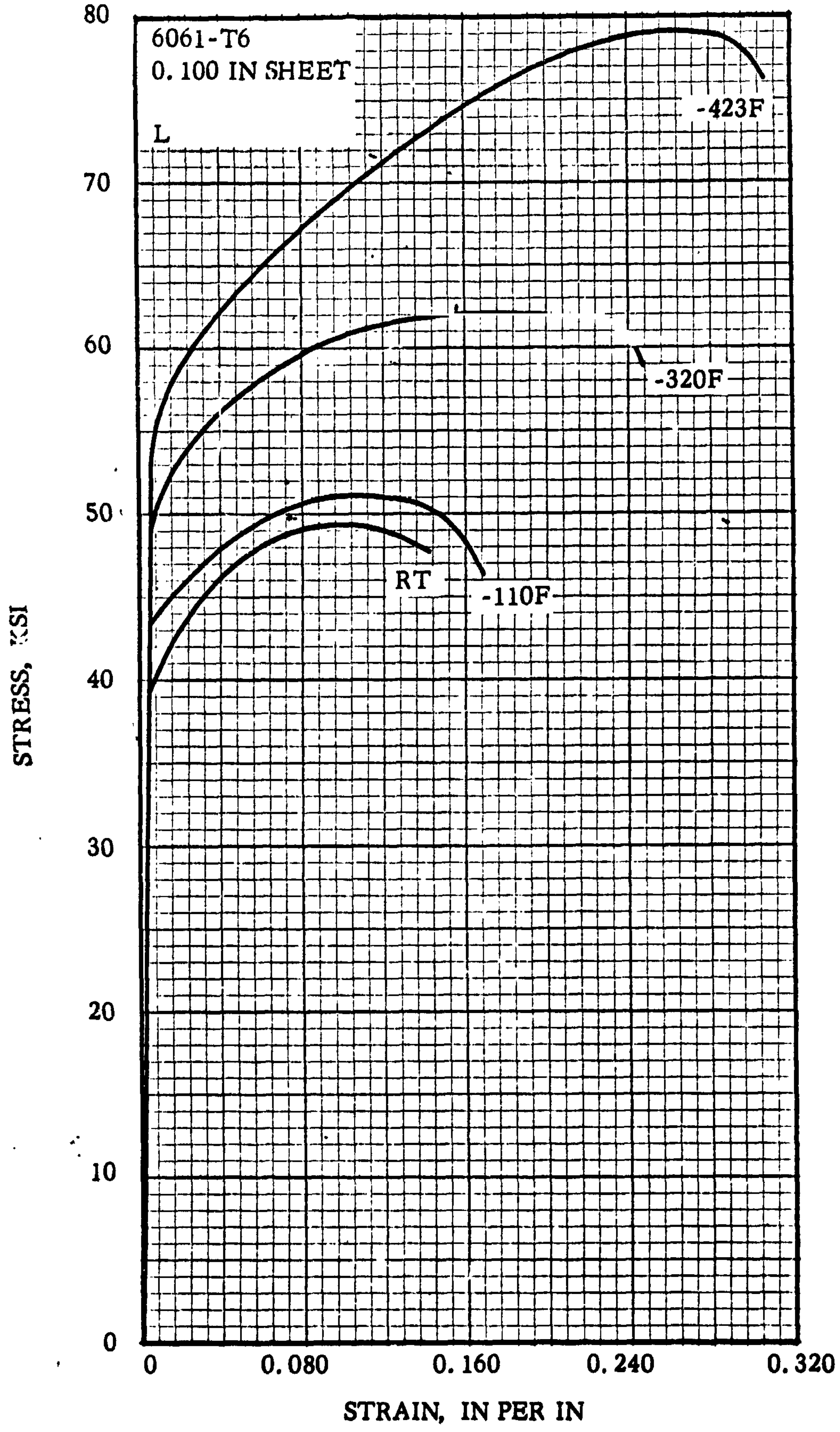


FIG. 7.4122 STRESS-STRAIN DIAGRAM FOR 0.100 IN SHEET AT ROOM AND LOW TEMPERATURE

(Ref. 7.9)

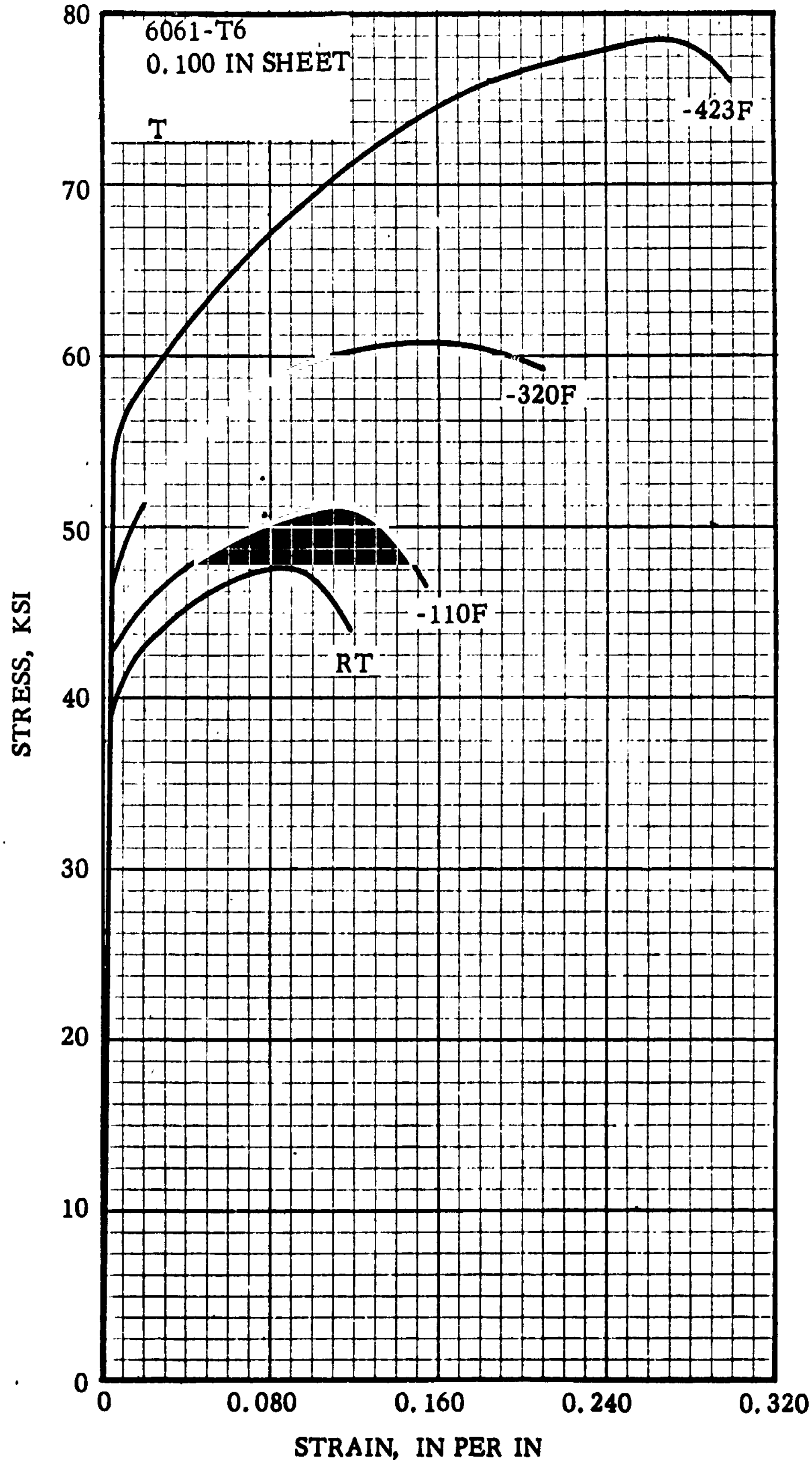


FIG. 7.4123 STRESS-STRAIN DIAGRAM FOR 0.100 IN SHEET AT ROOM AND LOW TEMPERATURE

(Ref. 7.9)

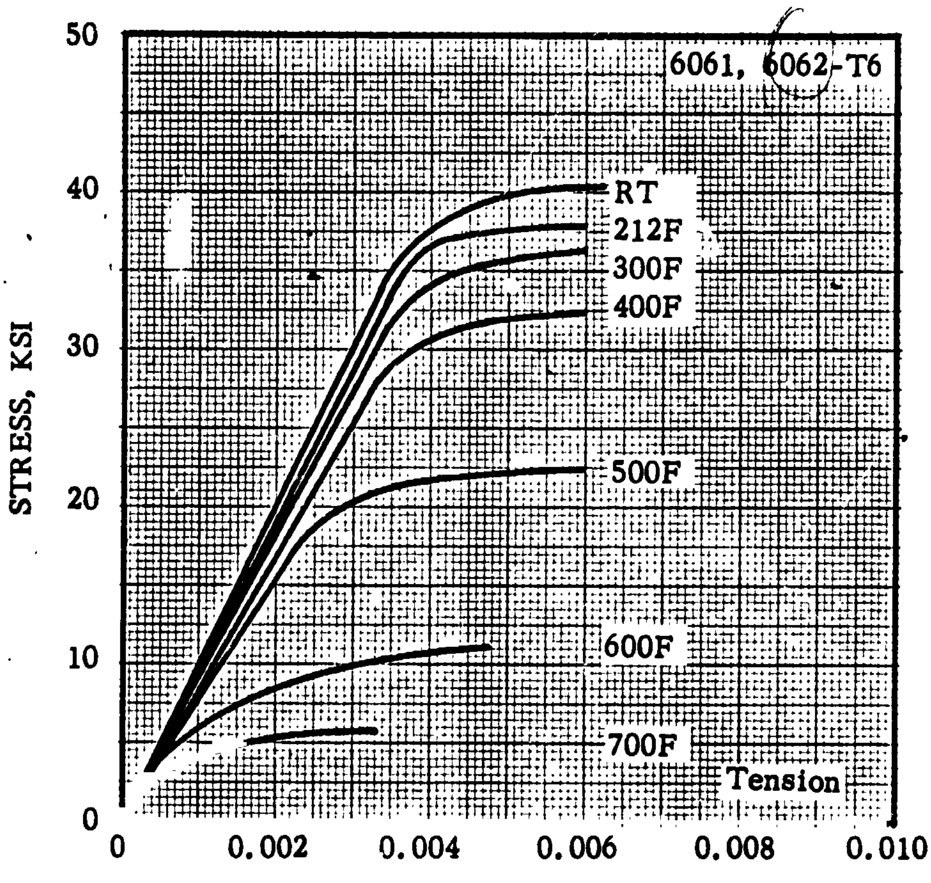


FIG. 7.4124 STRESS-STRAIN CURVES FOR 6061, 6062 IN T6 CONDITION

(Ref. 7.8)

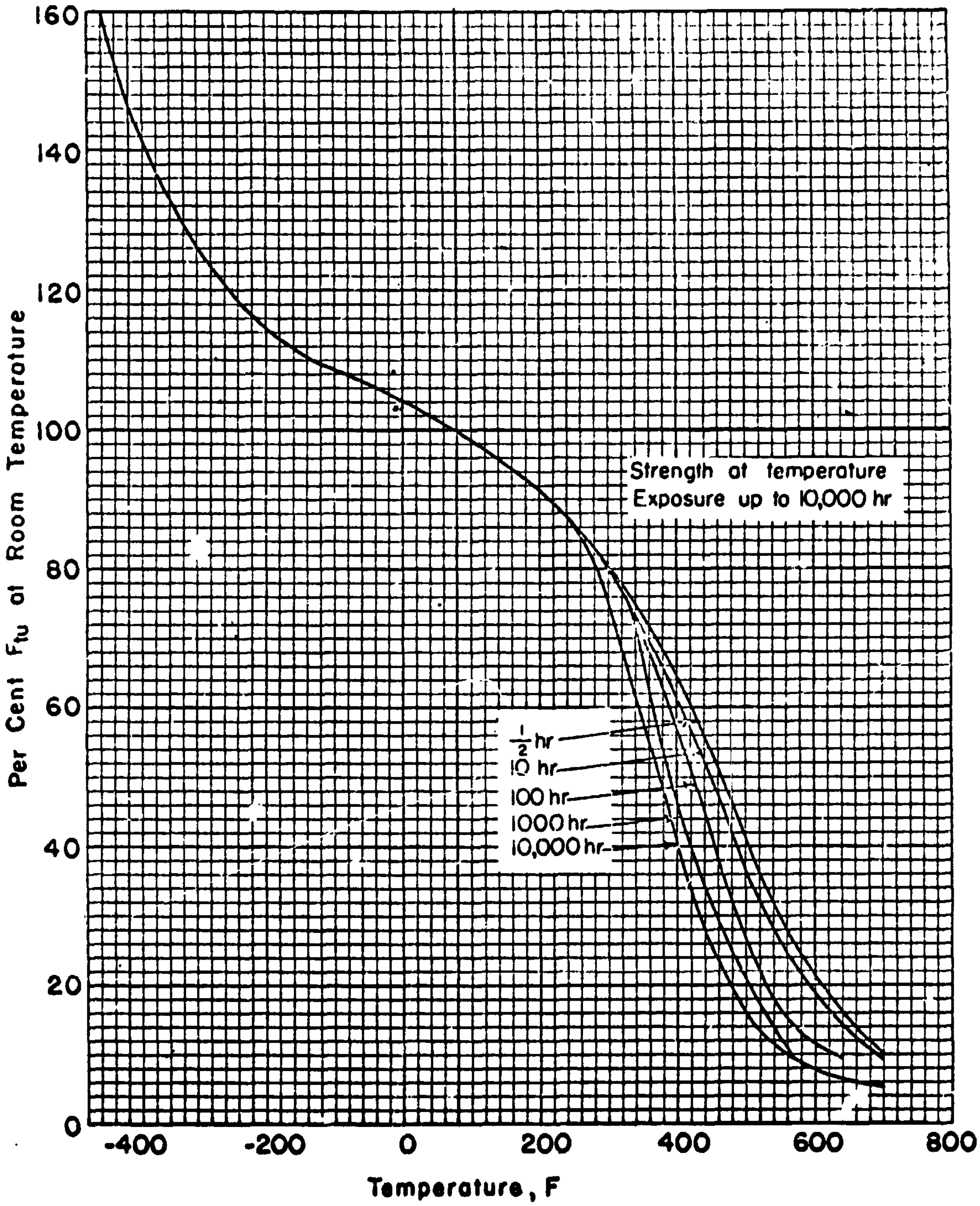


FIG. 7.4131 EFFECT OF TEMPERATURE ON ULTIMATE TENSILE STRENGTH (ALL PRODUCTS) OF ALLOY IN T6 CONDITION (Ref. 7.4)

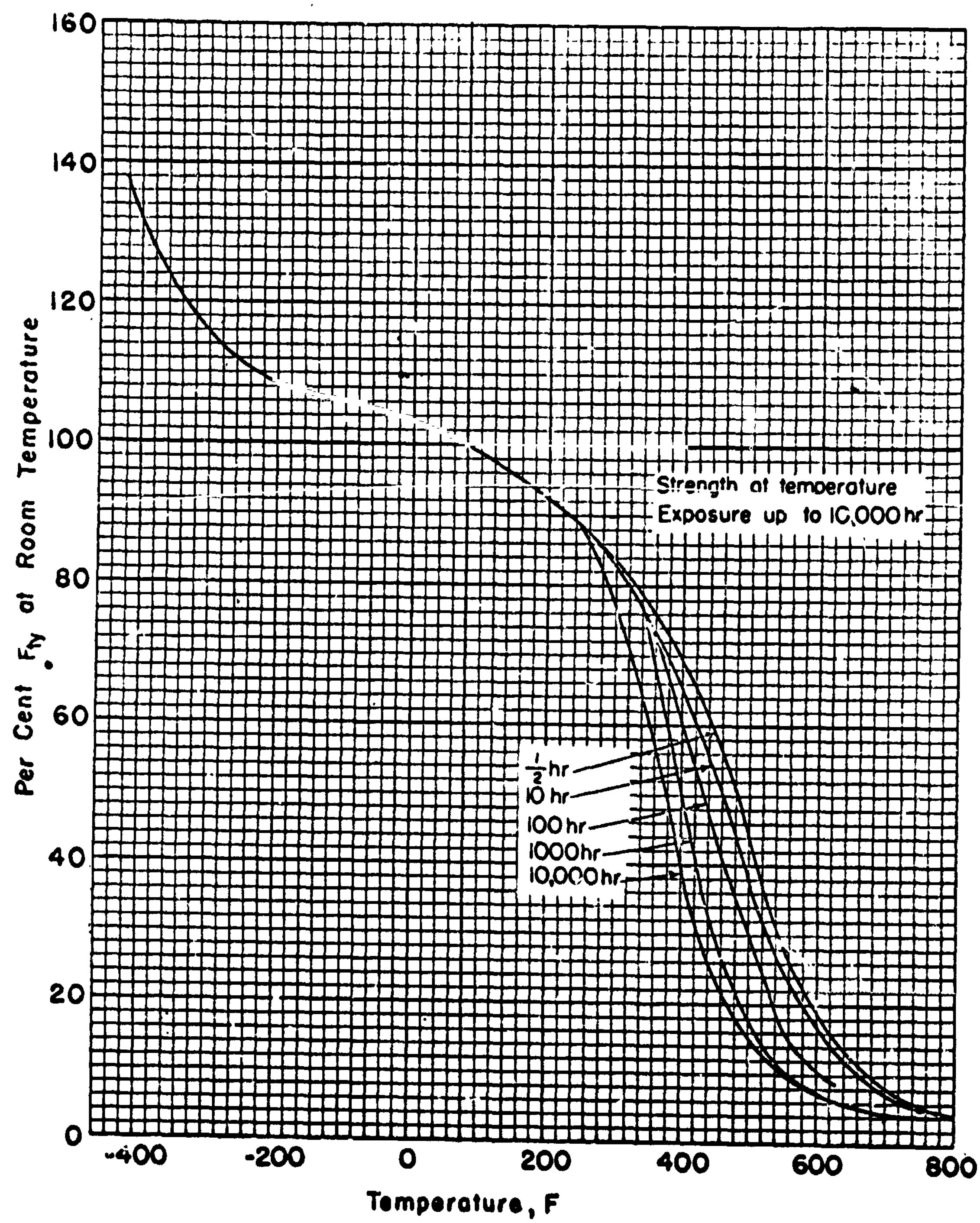


FIG. 7.4132 EFFECT OF TEMPERATURE ON TENSILE YIELD STRENGTH (ALL PRODUCTS) OF ALLOY IN T6 CONDITION

(Ref. 7.4)

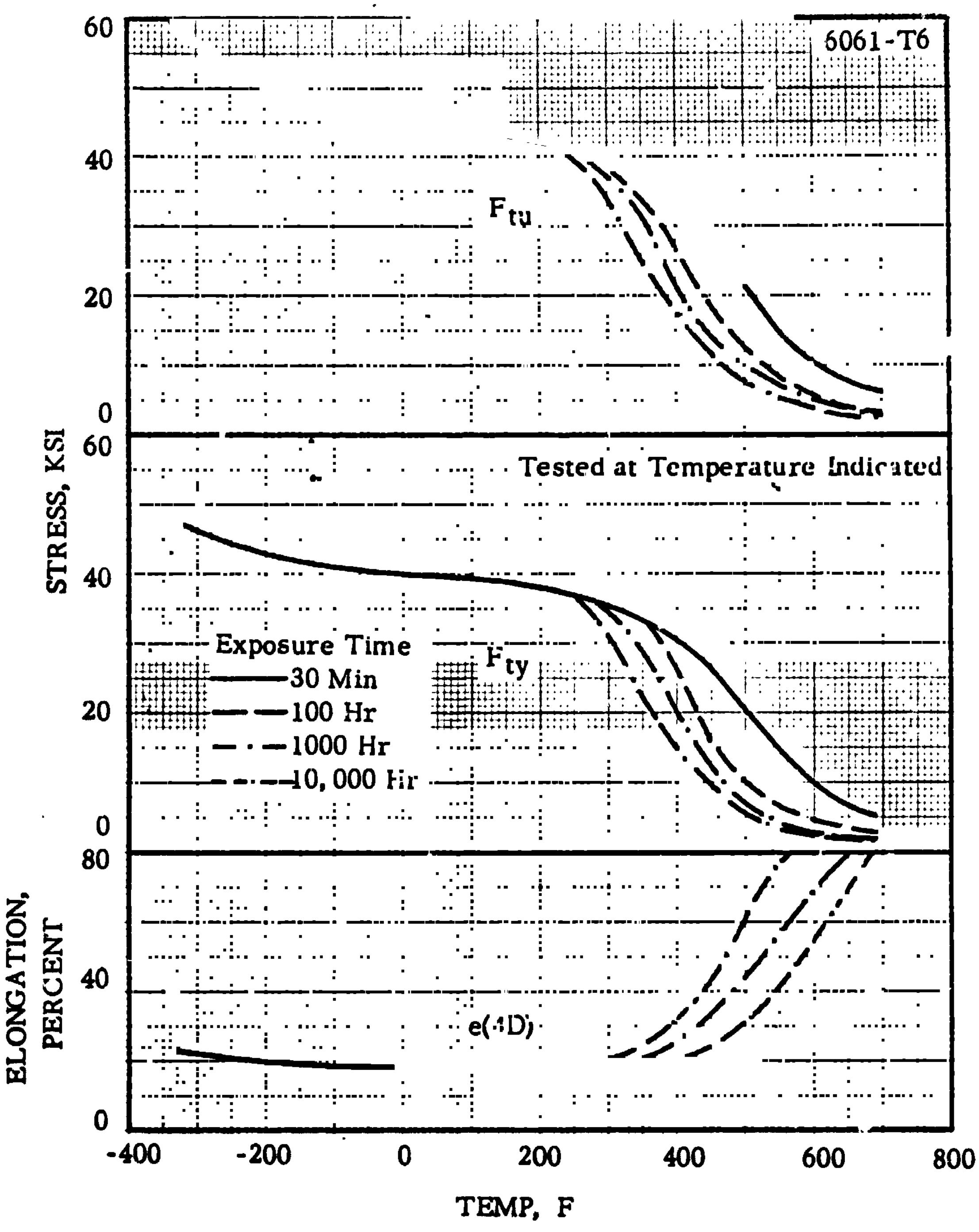


FIG. 7.4133 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON TENSILE PROPERTIES OF 6061 IN T6 CONDITION

(Ref. 7.10)

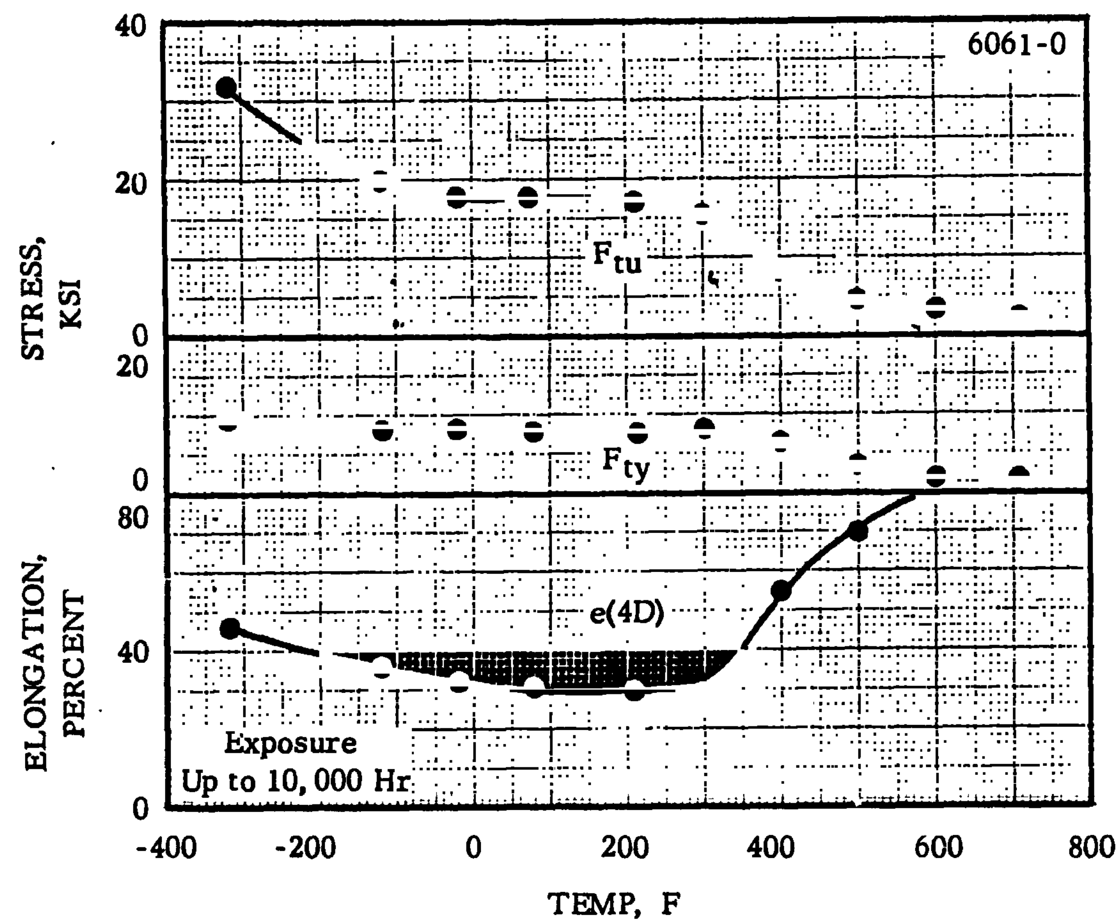


FIG. 7.4134 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON TENSILE PROPERTIES OF 6061 IN 0 CONDITION

(Ref. 7.11)

Feb- 1956 data
same fig in
ASP handbook

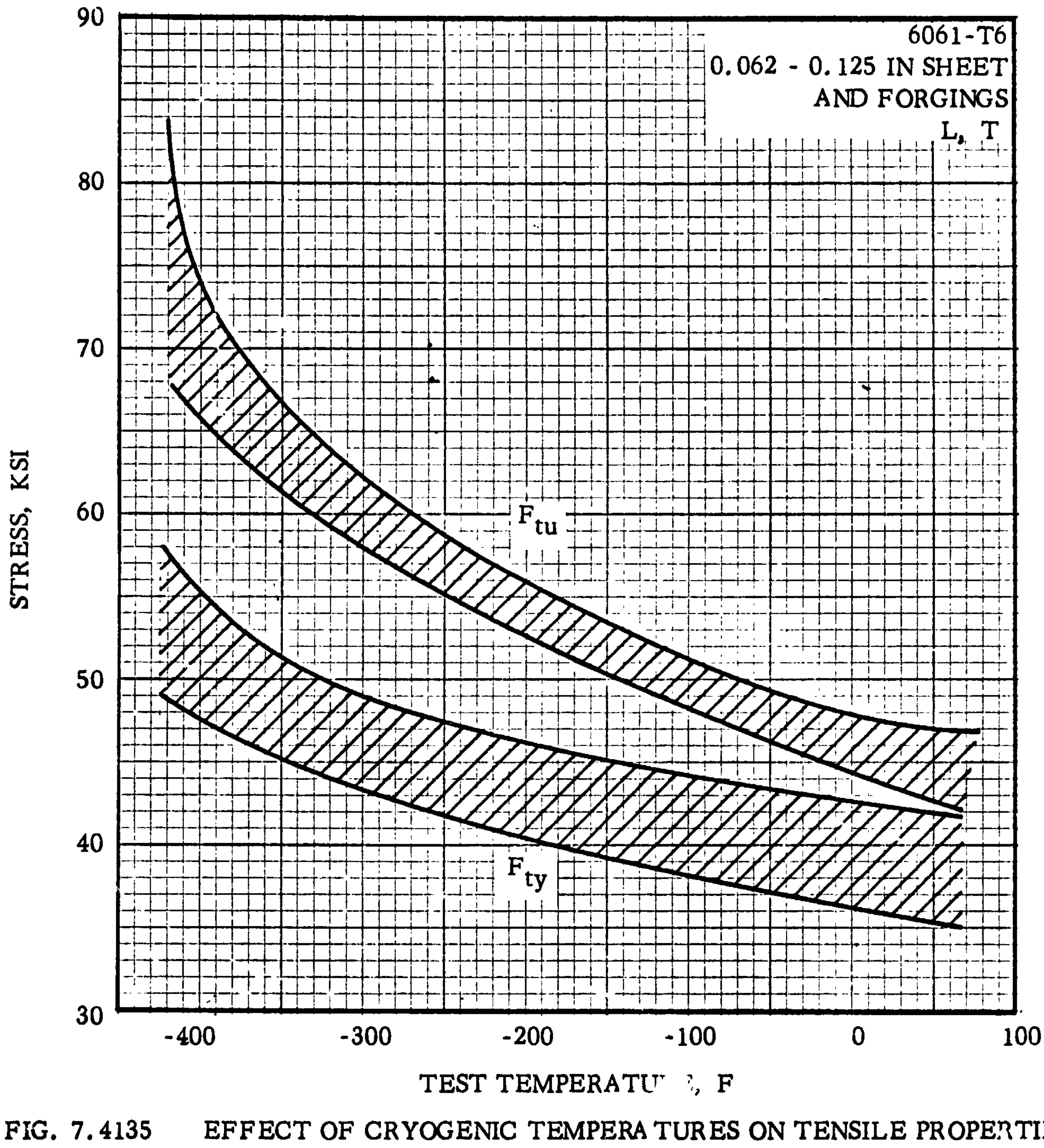


FIG. 7.4135 EFFECT OF CRYOGENIC TEMPERATURES ON TENSILE PROPERTIES OF T6 SHEET AND FORGINGS

(Refs. 7.9, 7.12, 7.13, 7.14)

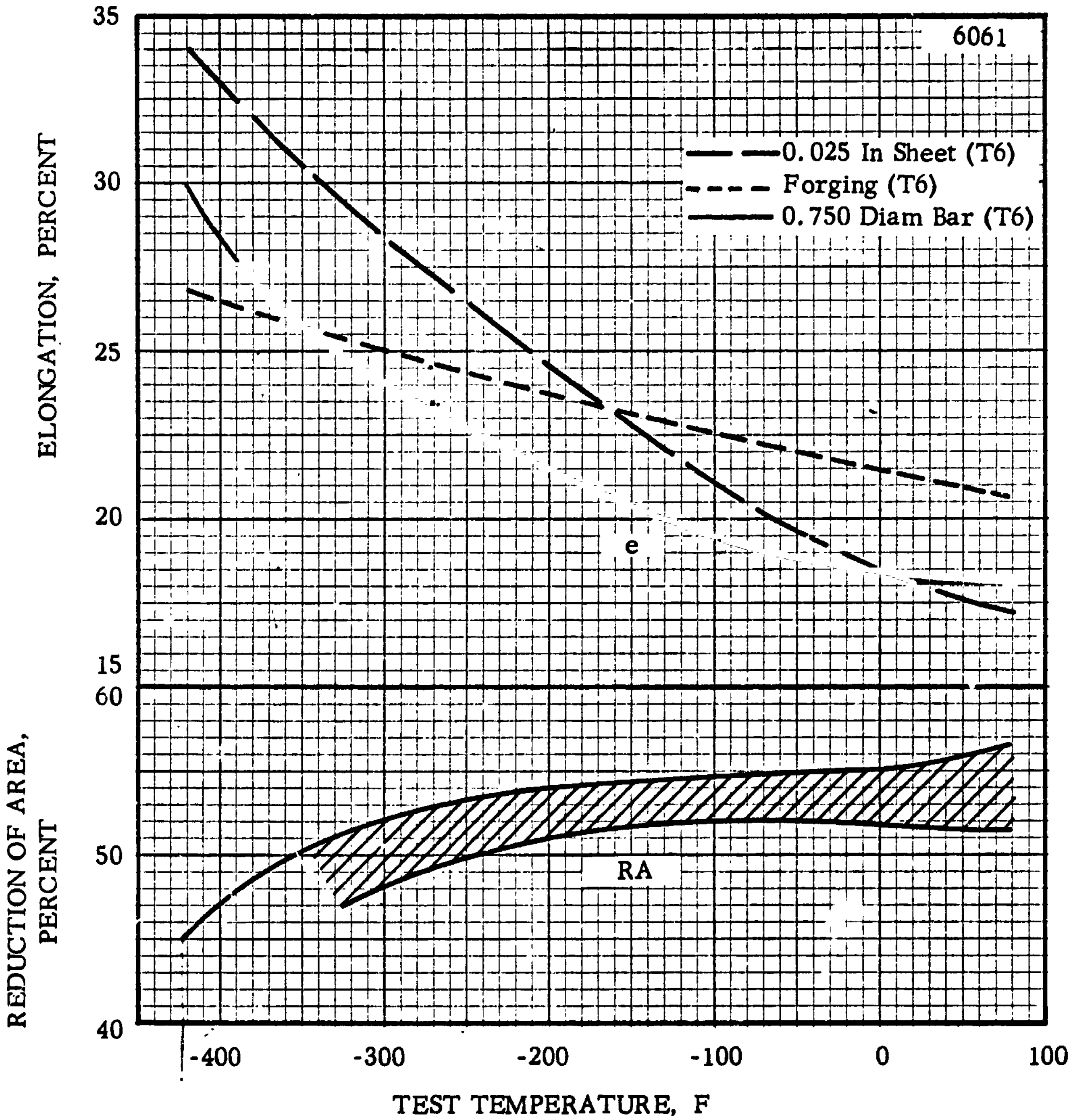


FIG. 7.4136 EFFECT OF CRYOGENIC TEMPERATURES ON TENSILE ELONGATION AND REDUCTION OF AREA

(Refs. 7.14, 7.15, 7.16, 7.17)

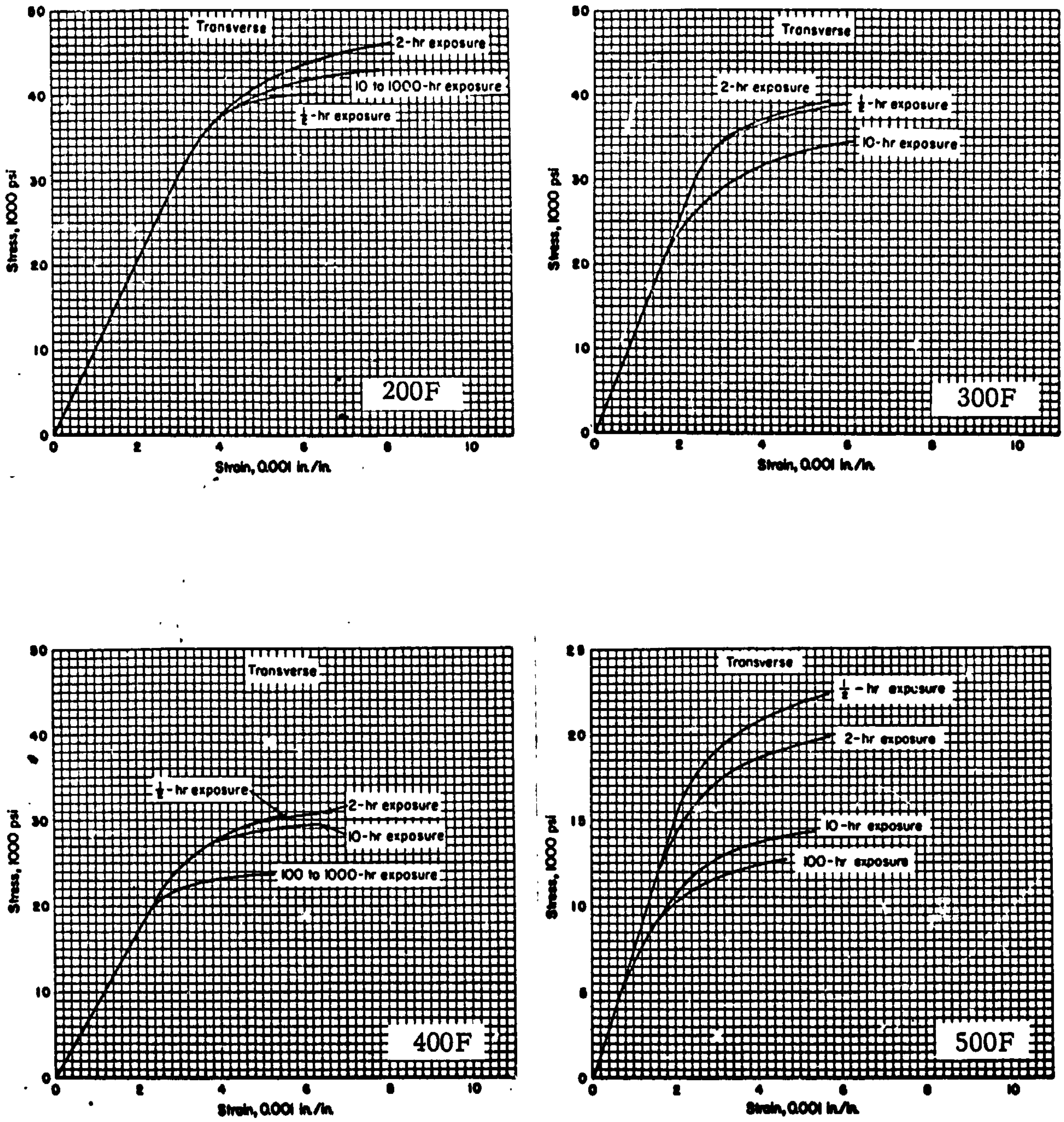


FIG. 7.4222 TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR T6 CLAD SHEET AT 200, 300, 400 AND 500F

(Ref. 7.4)

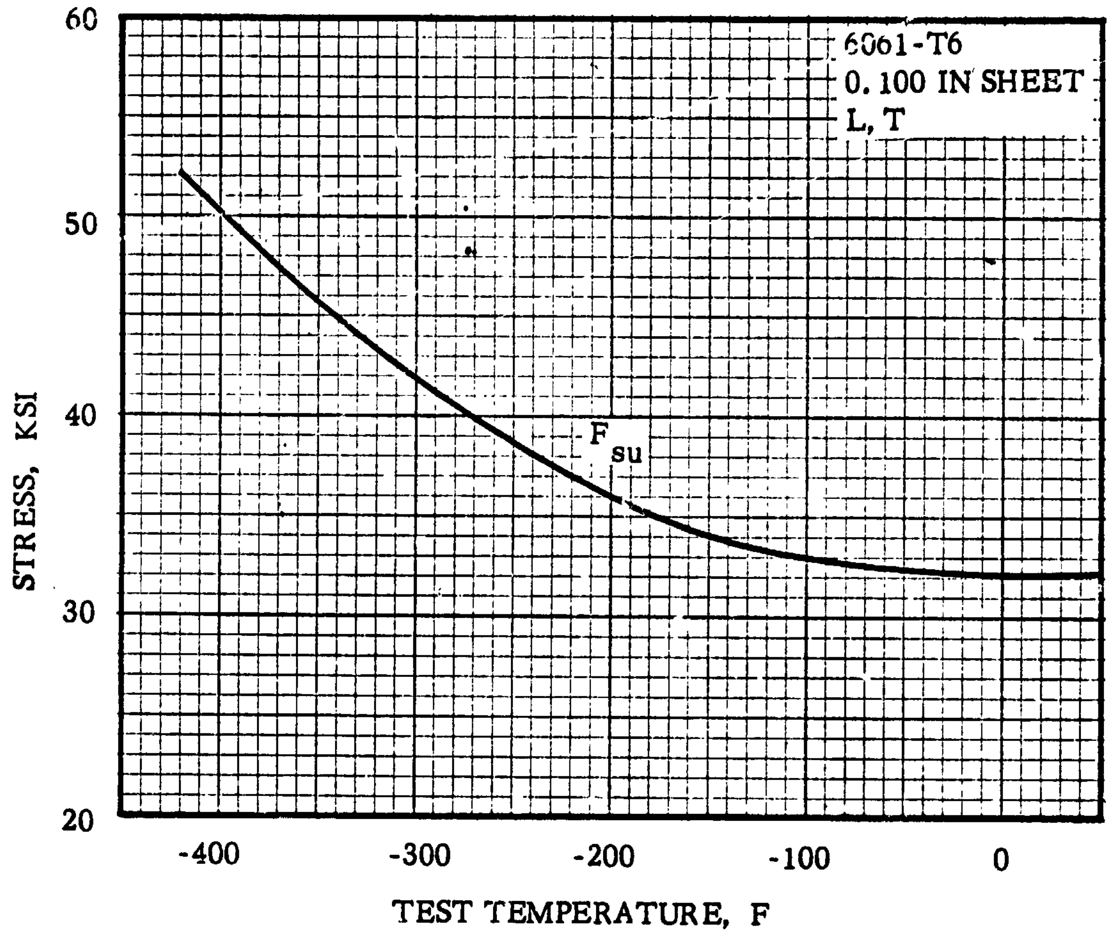
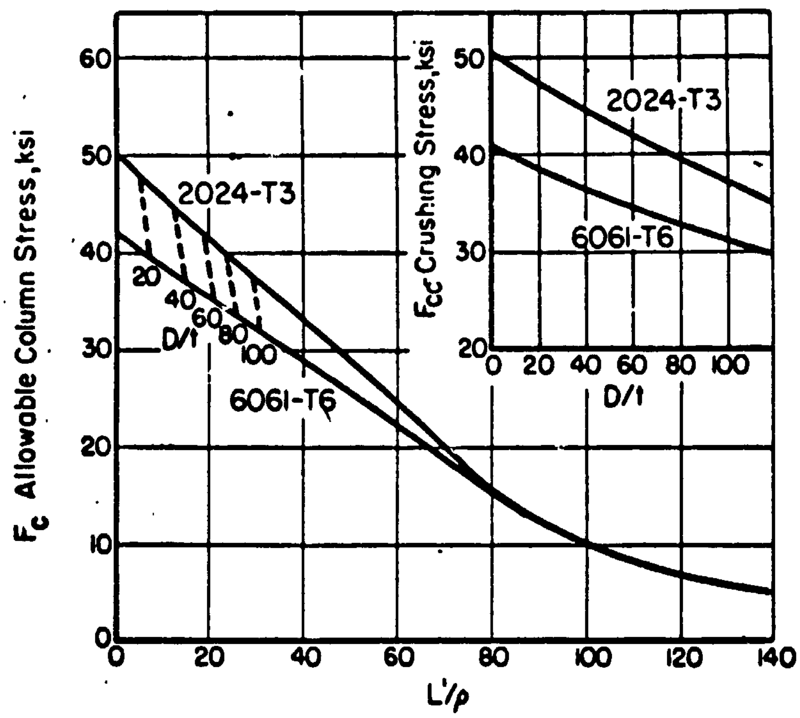


FIG. 7.4413 EFFECT OF LOW TEMPERATURE ON SHEAR STRENGTH OF SHEET IN T6 CONDITION

(Ref. 7.9)



(a) Round 2024 and 6061 Tubing

FIG. 7.4513 ALLOWABLE COLUMN AND CRUSHING STRESSES FOR TUBING

(Ref. 7.4)

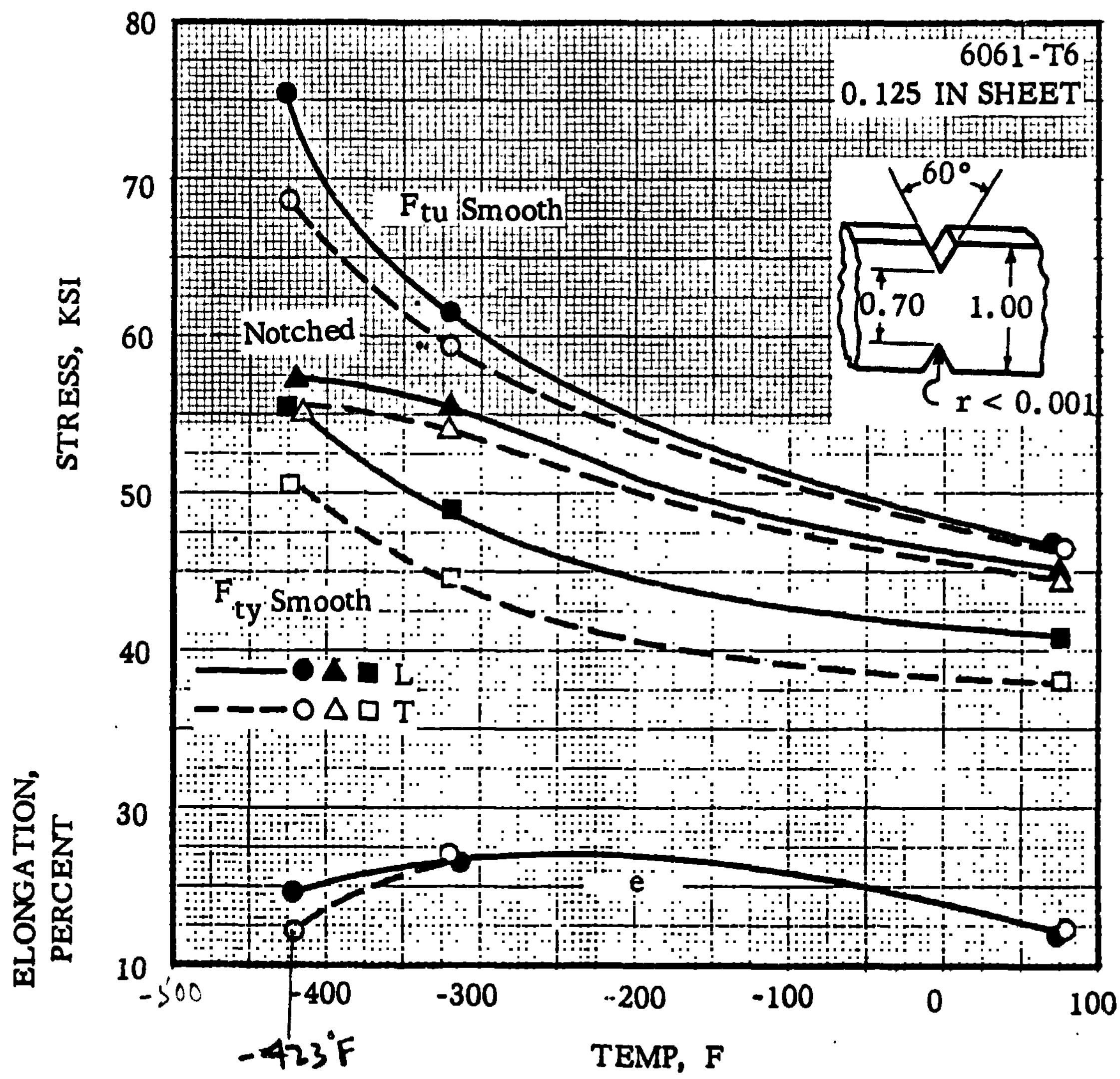


FIG. 7.4611 EFFECT OF TEST TEMPERATURE ON SMOOTH AND NOTCHED TENSILE PROPERTIES OF 6061 SHEET IN T6 CONDITION

(Ref. 7.12)

1960 data
same figure in
ASD handbook

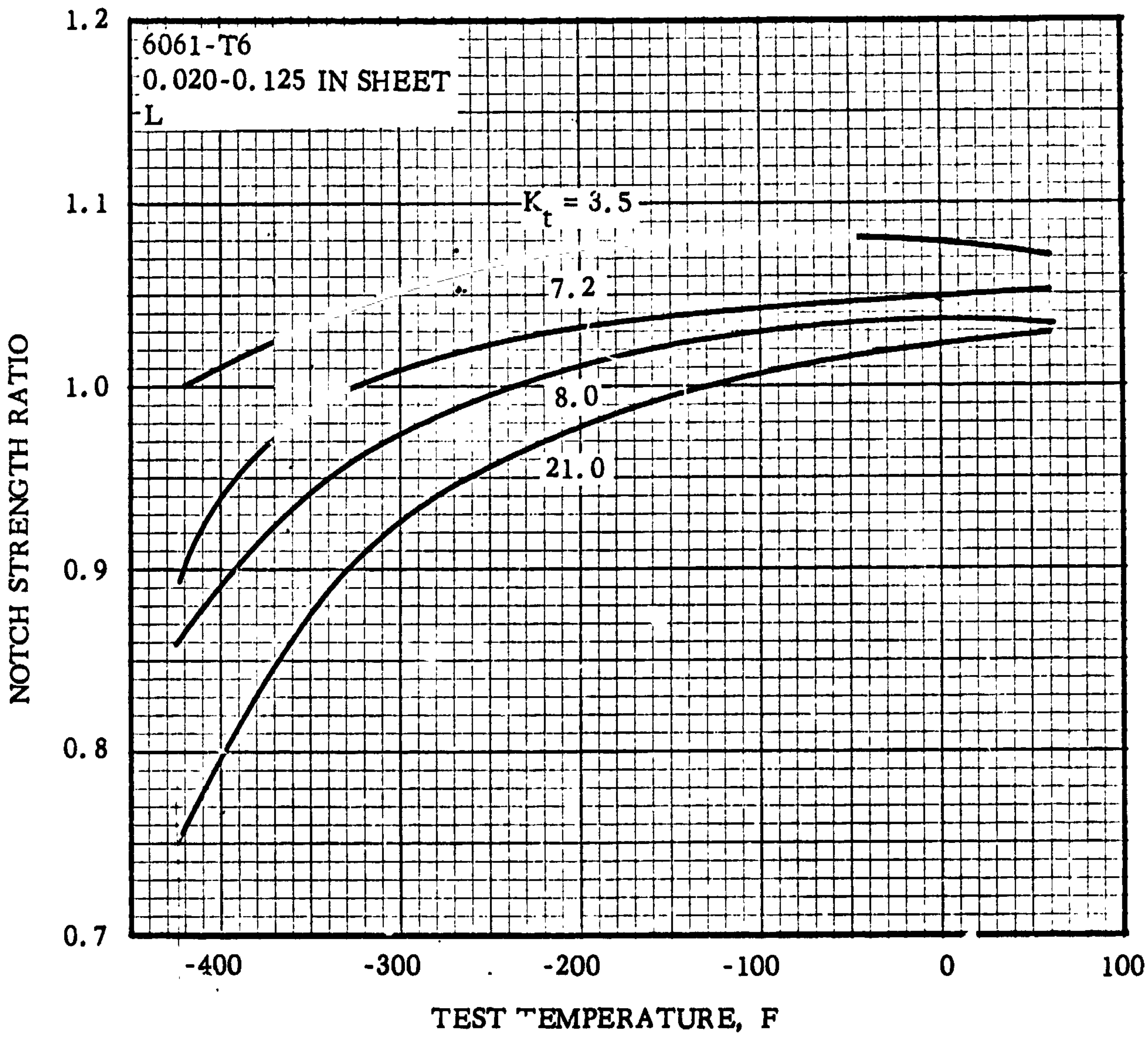


FIG. 7.4612 EFFECT OF CRYOGENIC TEMPERATURES ON NOTCH STRENGTH RATIO OF T6 SHEET

(Refs. 7.9, 7.12, 7.18)

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7.20 H. L. Johnson and H. E. Brooks, "Impact Strength of Various Metals at Temperatures Down to 20° Absolute", Tech. Report 264-17, Ohio State Univ. Res. Found., (May 1952)

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CHAPTER 8

DYNAMIC AND TIME DEPENDENT PROPERTIES

8.1 General

8.2 Specified Properties

8.3 Impact
8.31 Effect of temperature on impact properties of 6061 in T6 Condition, Fig. 8.31.
8.32 Effect of cryogenic temperature on impact strength of T6 bar and plate, Fig. 8.32.

8.4 Creep
8.41 Creep and creep rupture properties of 6061 and 6062 in T6 Condition at 212 to 500F, Fig. 8.41.

8.5 Stability
8.51 Effect of exposure to elevated temperature on room temperature tensile properties of 6061, 6062 in T4 Condition, Fig. 8.51.
8.52 Effect of exposure to elevated temperature on room temperature tensile properties of 6061, 6062 in T6 Condition, Fig. 8.52.

8.6 Fatigue
8.61 Rotating beam fatigue strength of alloy in T6 Condition, Fig. 8.61.
8.62 Cantilever beam fatigue strength of alloy at elevated temperatures, Fig. 8.62.
8.63 Typical constant life fatigue diagram for various products, Fig. 8.63.
8.64 Fatigue strength of sharply notched and smooth machined round specimens under completely reversed flexure, Fig. 8.64.
8.65 S-N curves at room temperature for T6 sheet and round specimens, Fig. 8.65.
8.66 S-N curves for bar at room temperature and cryogenic temperatures, Fig. 8.66.

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7.5 "Alcoa Aluminum Handbook", Aluminum Co. of America, (1962)

7.6 "The Aluminum Data Book", Reynolds Metals Co., (1965)

7.7 B. M. Loring, W. H. Baer and G. M. Carlton, "The Use of the Joining Test in Studying Commerical Age-Hardening Aluminum Alloys", AIME Metal Technology TP 2337, (February 1948)

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7.9 Data obtained for Cryogenic Materials Data Handbook by Martin Co. -Denver, under Air Force Contract AF 33(657)-9161

7.10 Alcoa Research Laboratories, "Mechanical Properties at Various Temperatures of 6061-T6 Products, Data Table, (December 1960)

7.11 Alcoa Research Laboratories, "Mechanical Properties at Various Temperatures of 6061-O", Data Sheet, (February 1956)

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7.13 R. Markovich and F. R. Schwartzberg, "Testing Techniques and Evaluation of Materials for Use at Liquid Hydrogen Temperature", ASTM STP 302, (1961)

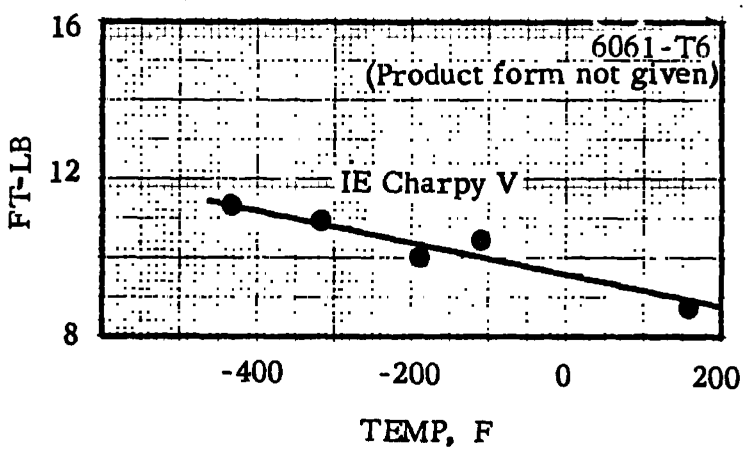

FIG. 8.31 EFFECT OF TEMPERATURE ON IMPACT PROPERTIES OF 6061 IN T6 CONDITION

(Ref. 8.1)

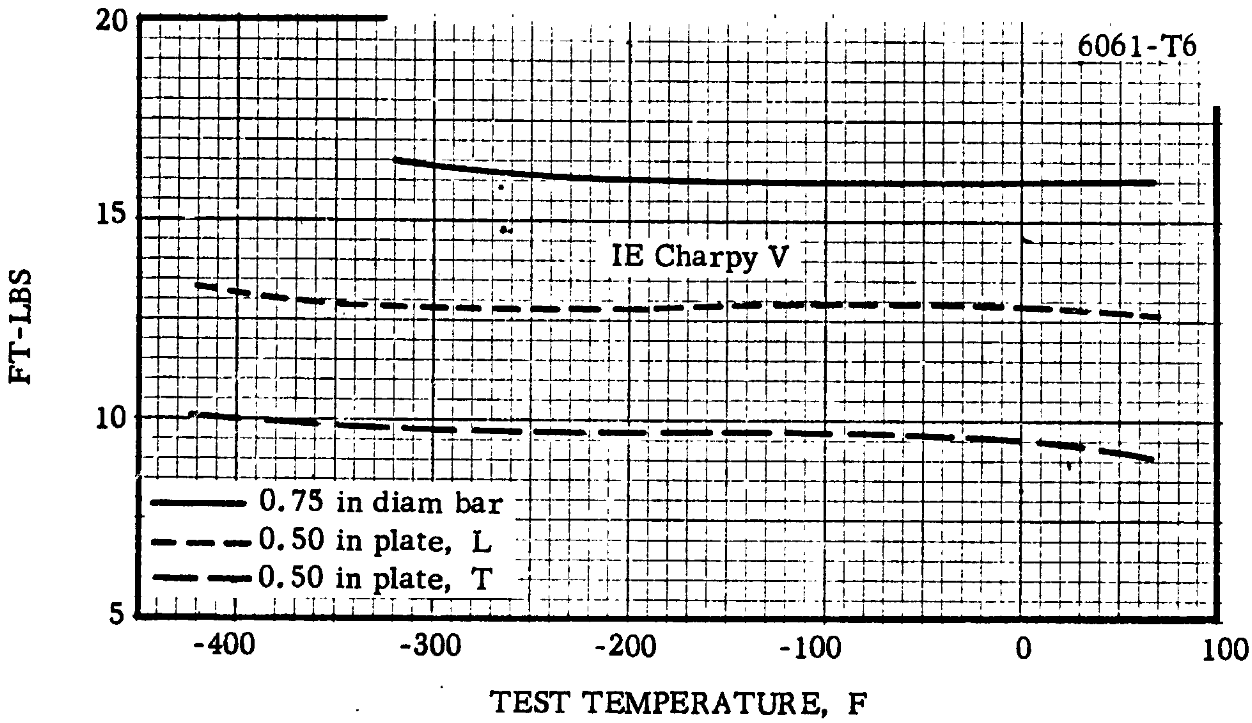

FIG. 8.32 EFFECT OF CRYOGENIC TEMPERATURES ON IMPACT STRENGTH OF T6 BAR AND PLATE

(Refs. 8.2, 8.3)

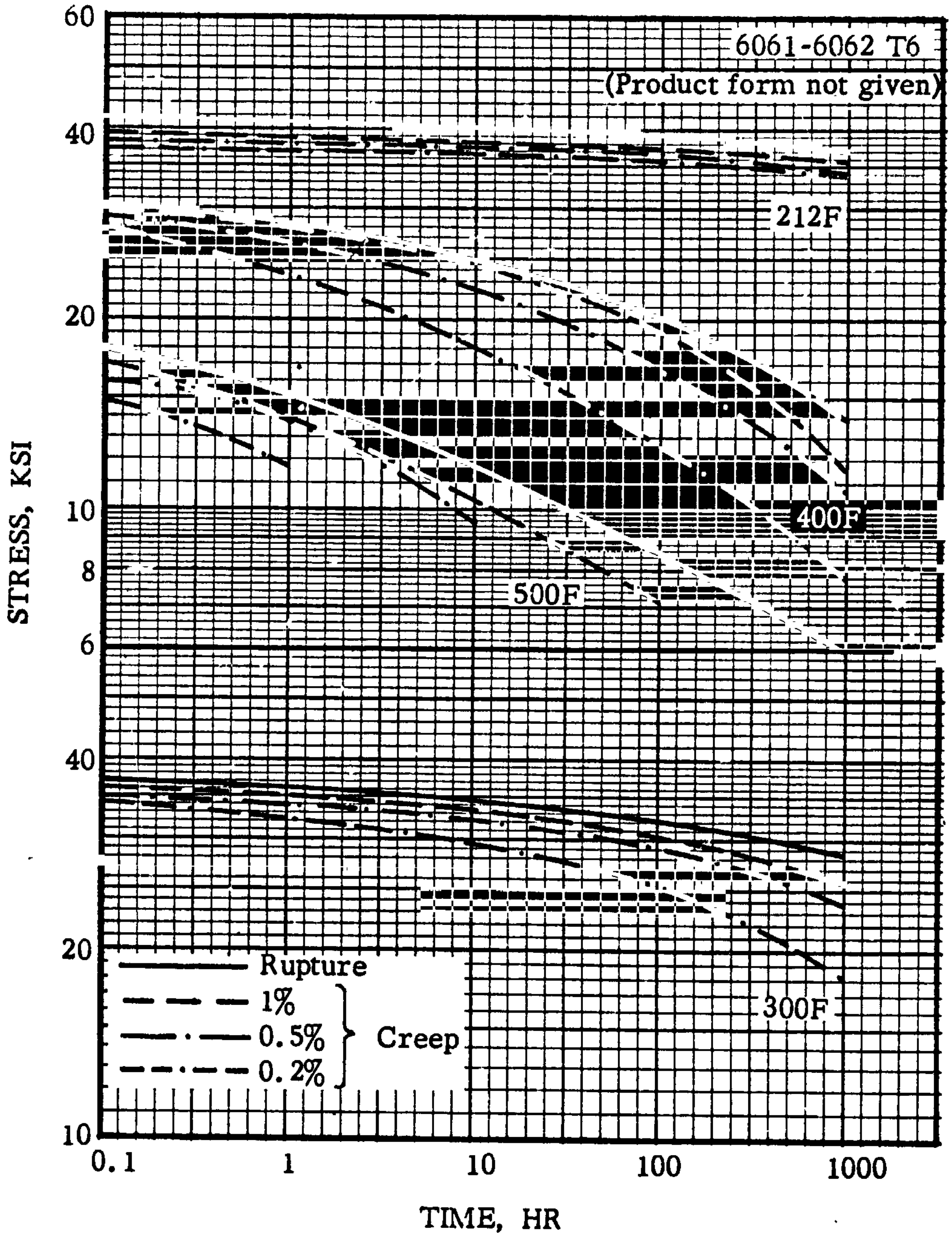

FIG. 8.41 CREEP AND CREEP RUPTURE PROPERTIES OF 6061 AND 6062 IN T6 CONDITION AT 212 TO 500F

(Ref. 8.4)

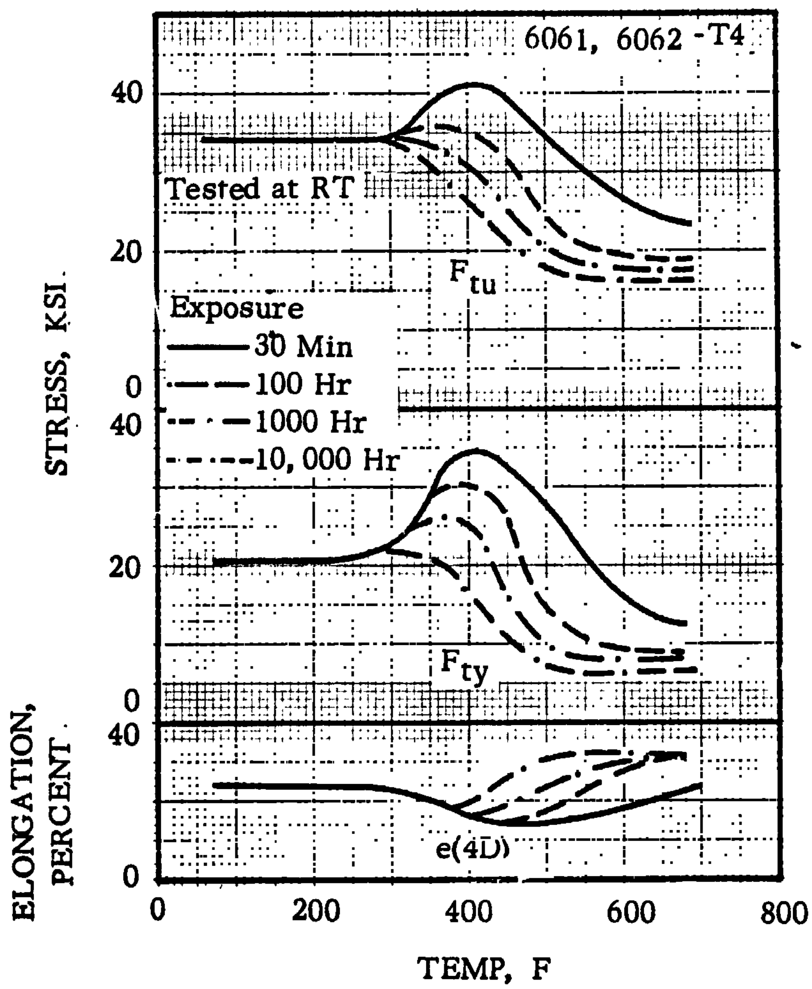

FIG. 8.51 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF 6061, 6062 IN T4 CONDITION

(Ref. 8.5)

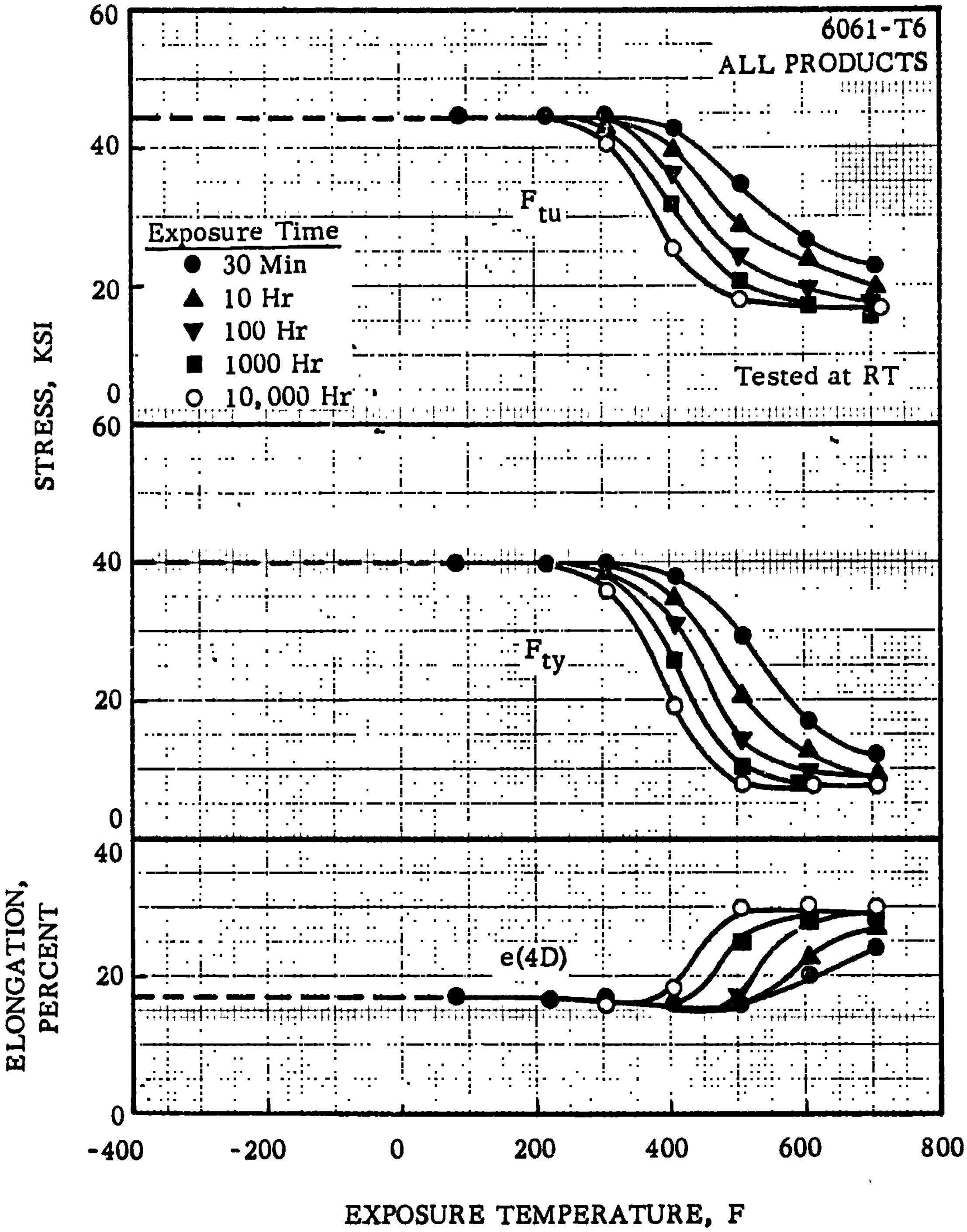

FIG. 8.52 EFFECT OF EXPOSURE TO ELEVATED TEMPERATURES ON ROOM TEMPERATURE TENSILE PROPERTIES (ALL PRODUCTS IN T6 CONDITION)

(Ref. 8.10)

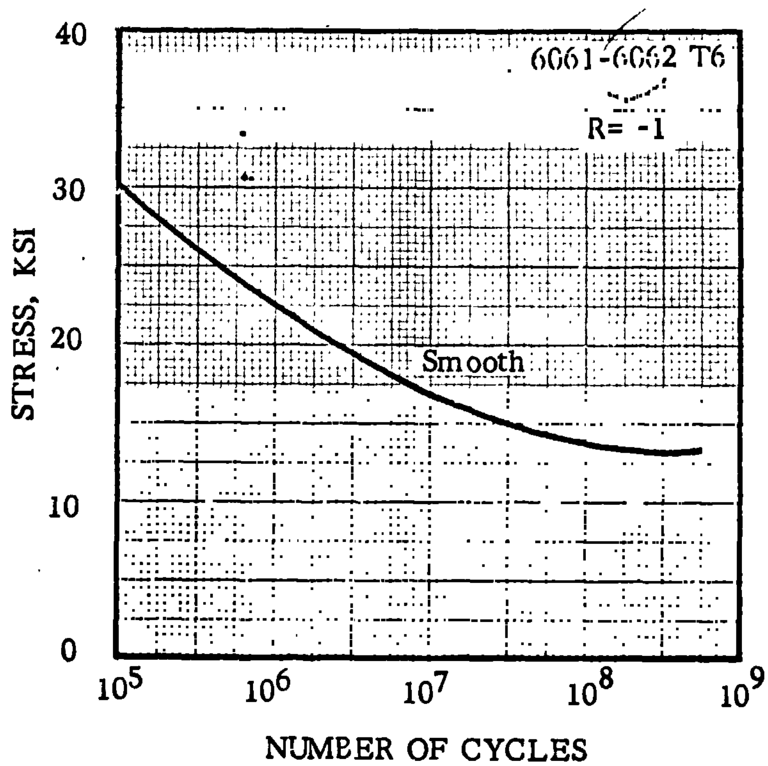

FIG. 8.61 ROTATING BEAM FATIGUE STRENGTH OF 6061 AND 6062 IN T6 CONDITION

(Ref. 8.4)

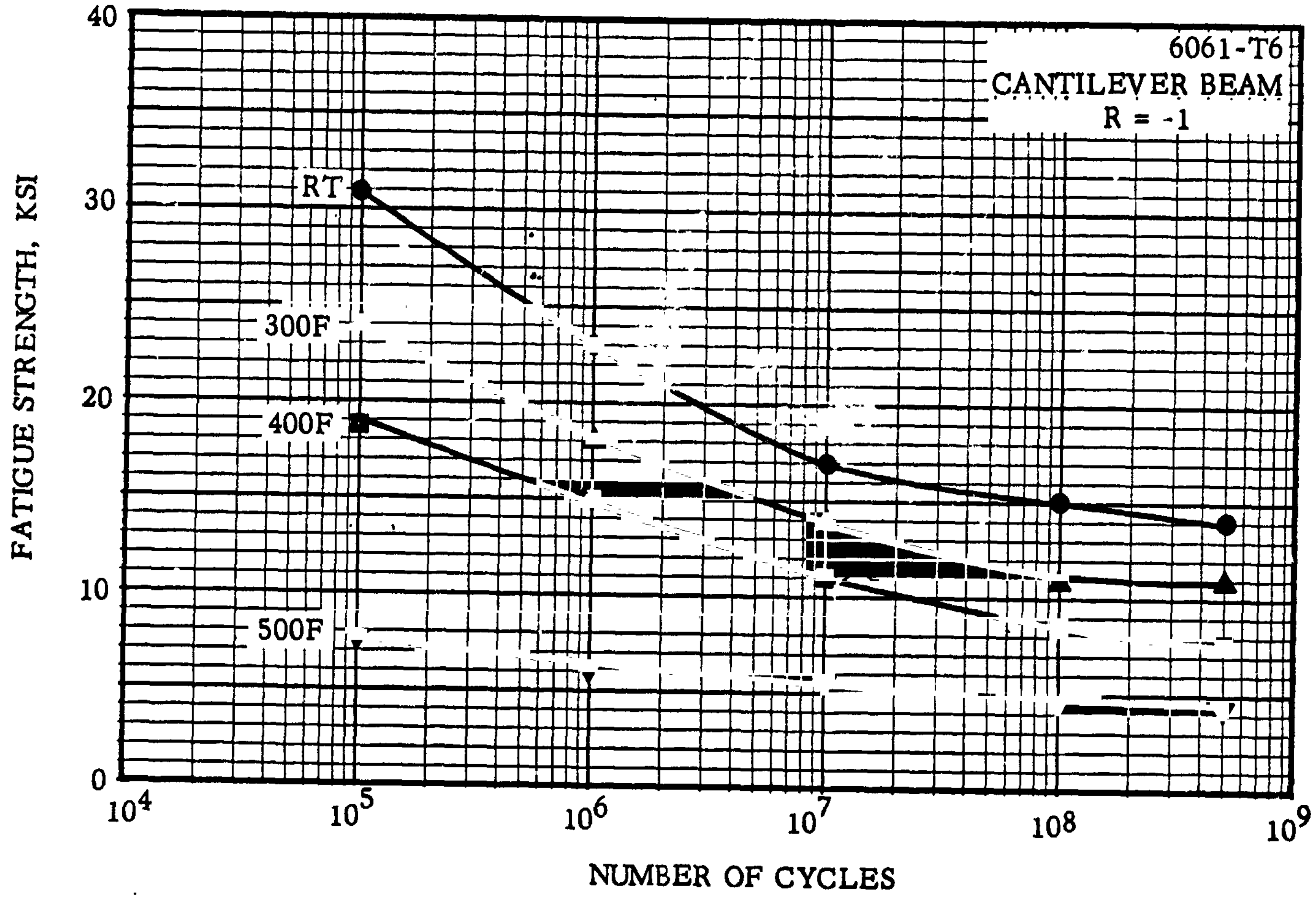

FIG. 8.62 CANTILEVER BEAM FATIGUE STRENGTH OF ALLOY AT ELEVATED TEMPERATURES

(Ref. 8.6)

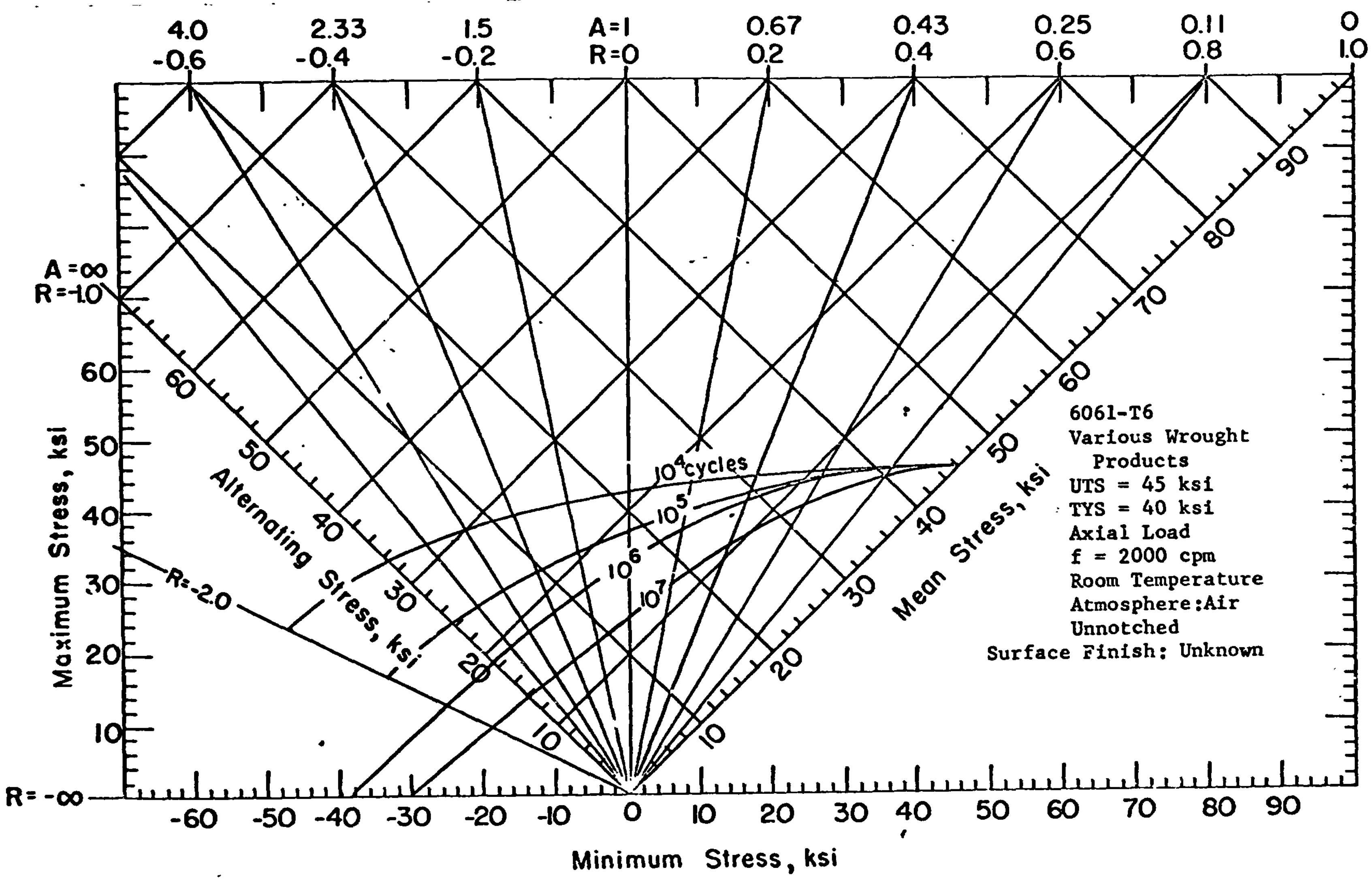

FIG. 8.63 TYPICAL CONSTANT - LIFE FATIGUE DIAGRAM FOR VARIOUS PRODUCTS (Ref. 8.6)

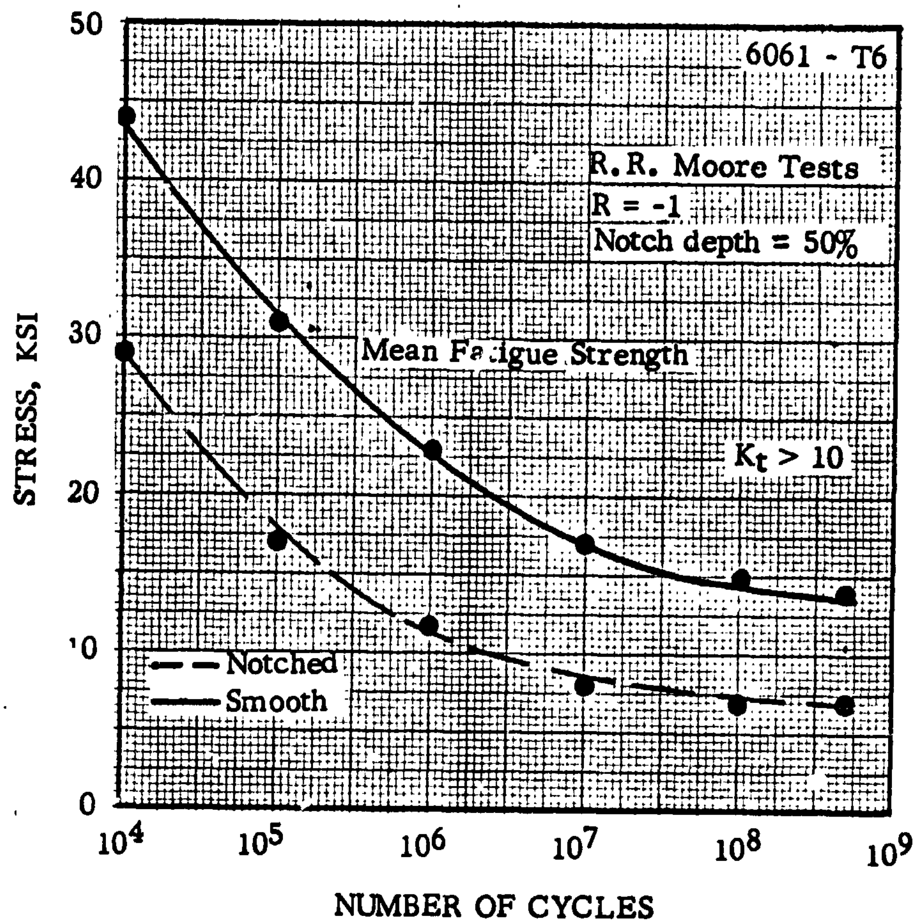

FIG. 8.64 FATIGUE STRENGTH OF SHARPLY NOTCHED AND SMOOTH MACHINED ROUND SPECIMENS UNDER COMPLETELY REVERSED FLEXURE

(Ref. 8.6)

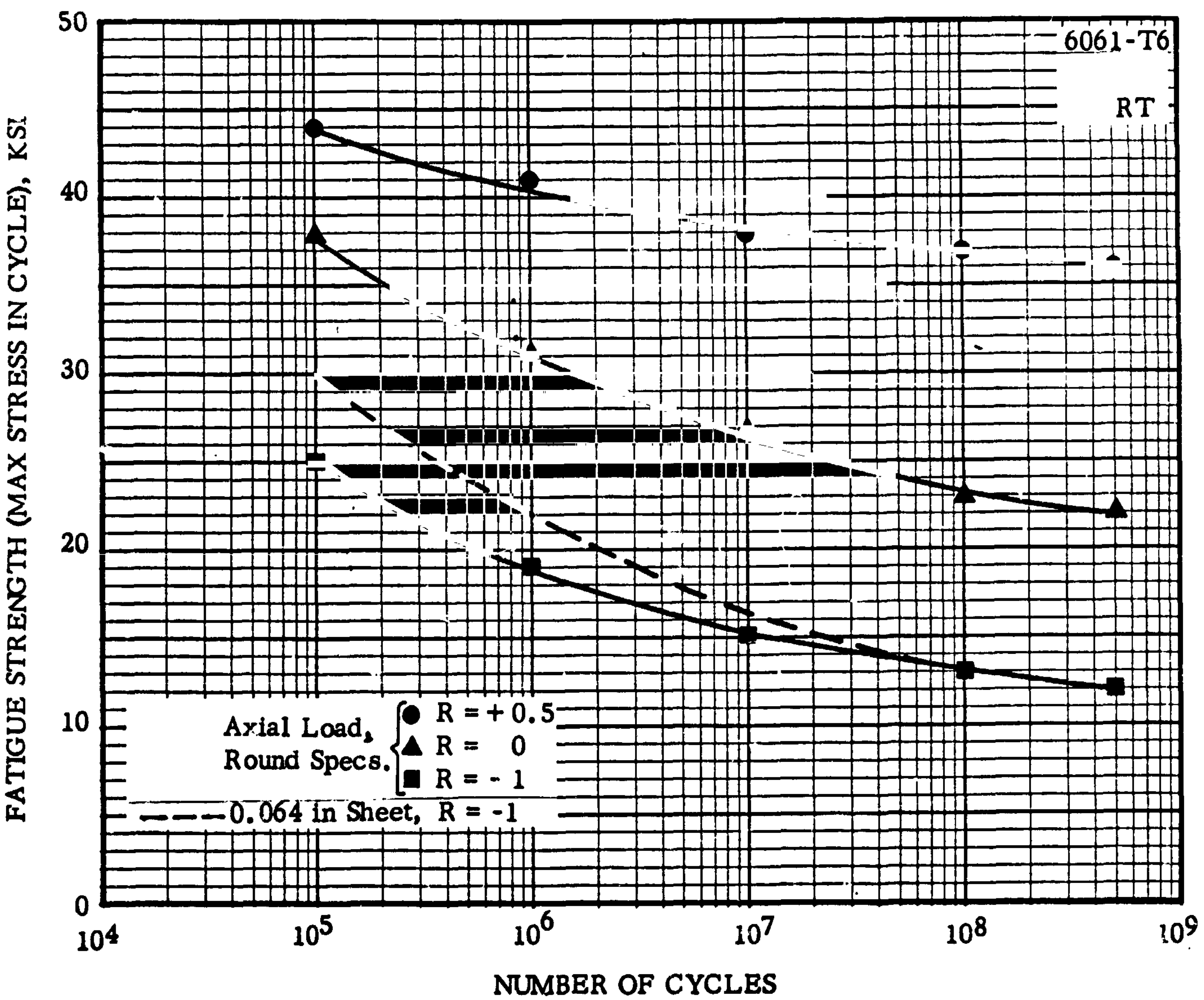

FIG. 8.65 S-N CURVES AT ROOM TEMPERATURE FOR T6 SHEET AND ROUND SPECIMENS (Ref. 8.6)

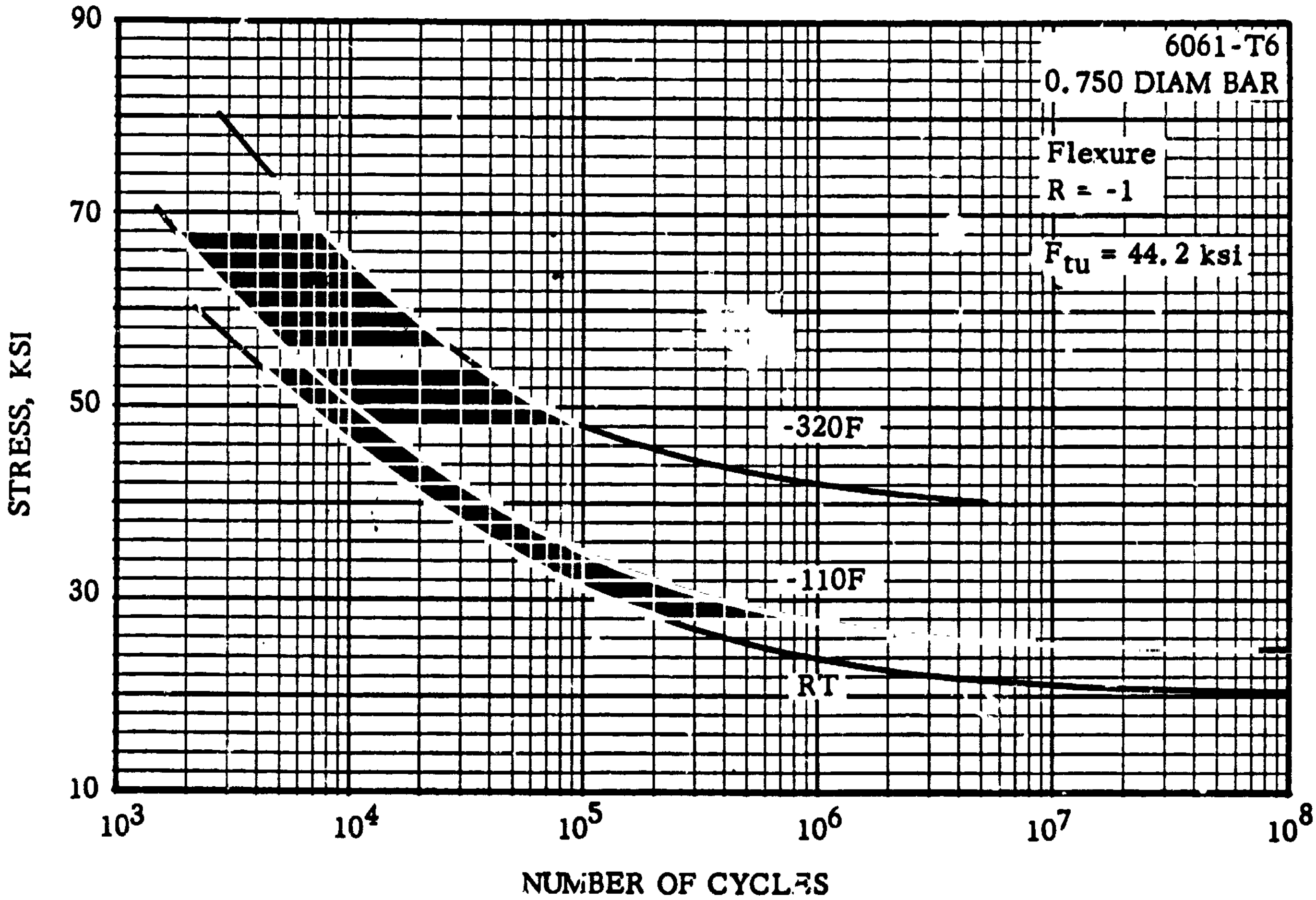

FIG. 8.66 S-N CURVES FOR BAR AT ROOM TEMPERATURE AND CRYOGENIC TEMPERATURES (Refs. 8.7, 8.8, 8.9)

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CHAPTER 9

PHYSICAL PROPERTIES

9.1 Density (ρ)

$0.098\ lb/in^3$ at 68F,

$2.70\ gr/cm^3$ at 20C, (Refs. 9.1, 9.2).

9.2 Thermal Properties

9.21 Thermal conductivity (K)

O temper	0.41 cal-cm/sec cm^2 C 99.2 Btu-ft/hr ft^2 F at 77F, (Ref. 9.2).
T4, T6 tempers	0.37 cal-cm/sec cm^2 C 89.5 Btu-ft/hr ft^2 F at 77F, (Ref. 9.2).

9.22 Thermal expansion (α), Fig. 9.22

68F to 212F	13.0×10^{-6} in/in/F, (Ref. 9.1)
20C to 100C	23.4×10^{-6} in/in/C.

9.221 Thermal expansion at low temperatures, Fig. 9.221.

9.23 Specific heat (c_p)

0.23 cal/gr C at 100C,

0.23 Btu/lb F at 212F, (Refs. 9.1, 9.2).

9.24 Thermal diffusivity. Data may be calculated according to the equation

Diffusivity = $K/\rho c_p$).

9.3 Electrical Properties

9.31 Electrical resistivity at RT.

O temper	1.51 microhm-inch
T4, T6 tempers	1.69 microhm-inch, (Ref. 9.2).

9.4 Magnetic Properties

9.41 Permeability. The alloy is nonmagnetic.

9.5 Nuclear Properties. The search for information on the nuclear physical constants of the 6061 alloy was not fruitful. Data was found on the 6063 aluminum alloy and because of the similarity in chemistry of the two alloys (both are aluminum-magnesium-silicide alloys) the data on 6063 is presented below:

9.51 (6063 Alloy)

Microscopic thermal-neutron cross section. 0.23 barns/atom,

Macroscopic thermal-neutron cross-section 0.012 reciprocal cm, (Ref. 9.5).

9.52 Effect of radiation on tensile properties, Table 9.52.

9.6 <u>Other Physical Properties</u>

9.61 Emissivity

In air at 77F: 0.035 to 0.07, (Ref. 9.7).

9.62 Damping capacity. (no data found).

TABLE 9.52

Source	Ref. 9.6	
Alloy	6061	
Data	Effect of Radiation on Tensile Properties	
Condition	0	T6
Exposure, 10^{18} n/cm^2	100	1170
Temp. F	149	120
Temp. C	65	49
F_{tu}, ksi; -control	18.1	47.2
-irradiated	37.3	51.9
F_{ty}, ksi; -control	9.5	40.0
-irradiated	25.6	42.8
e(total, percent; -control	28.8	21.0
-irradiated	22.4	22.0

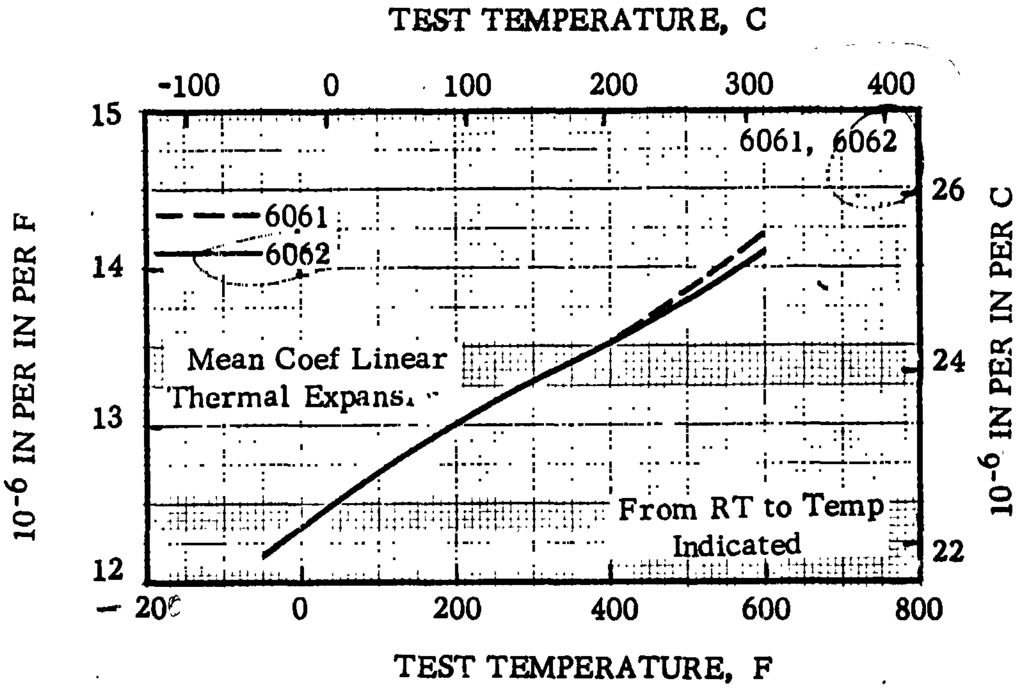

FIG. 9.22 THERMAL EXPANSION

(Ref. 9.3 and 9.4)

figure in ASD handbook

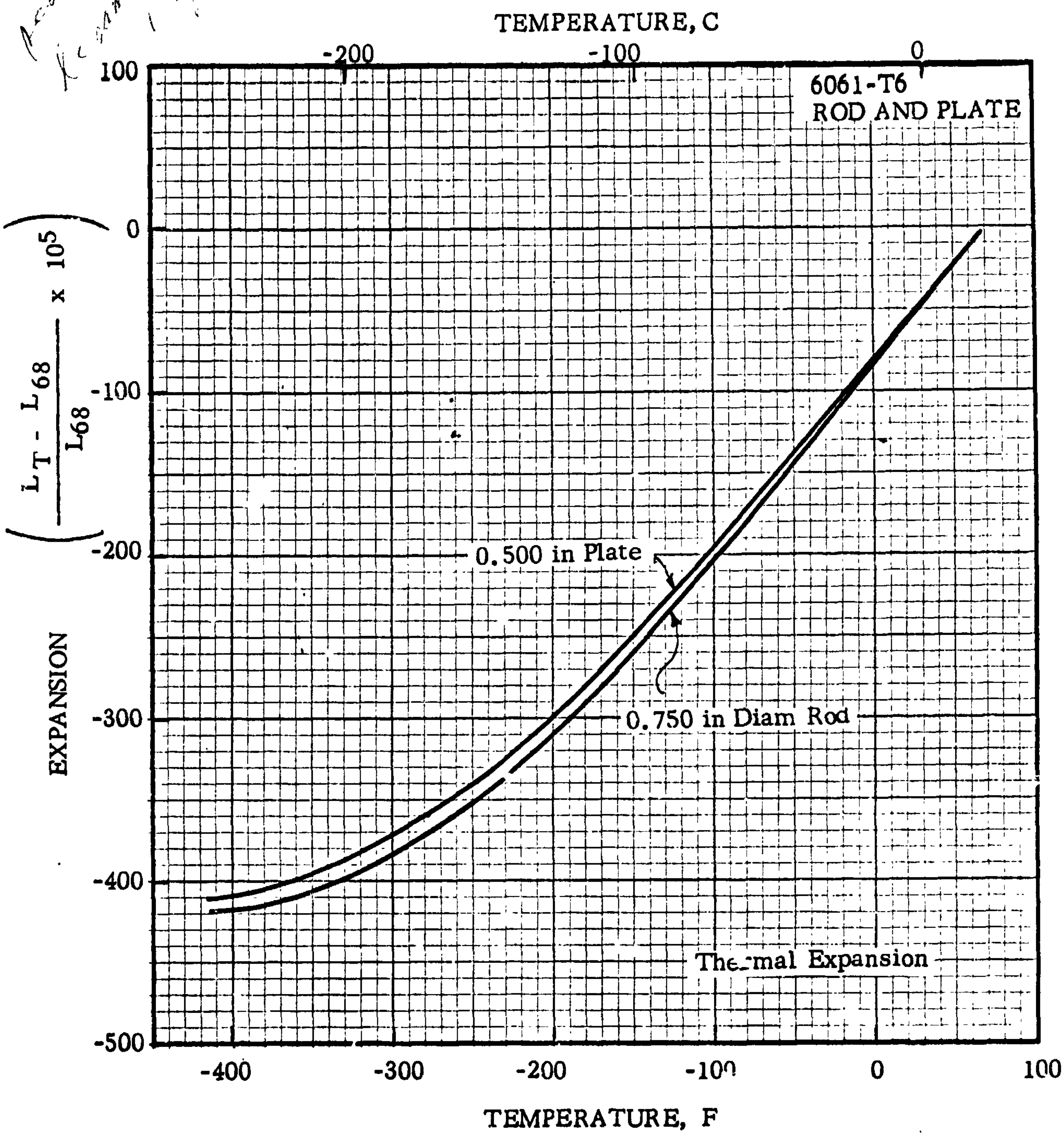

FIG. 9.221 THERMAL EXPANSION AT LOW TEMPERATURES

(Refs. 9.8 and 9.9)

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9.6 "Materials in Design Engineering", Materials Selector Issue, (Mid-October 1964)

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CHAPTER 10

CORROSION RESISTANCE AND PROTECTION

10.1 General. Despite its high chemical reactivity and affinity for oxygen, aluminum exhibits excellent corrosion resistance in most common environments, because it passivates spontaneously and very rapidly under normal oxidizing conditions. The passive film is a hard, strongly adhering layer of aluminum oxide, estimated as 20-100Å thick on aluminum exposed to air, (Ref. 10.1), which protects the metal from direct attack. Thus the corrosion rate of aluminum generally decreases with time, except under severe or specific exposure conditions which tend to disrupt the passive film. Outdoors, aluminum and its alloys weather to a pleasant gray color, with some initial superficial pitting which gradually ceases, (Ref. 10.2). Industrial soot, sulfur dioxide, sulfur trioxide and marine spray tend to increase atmospheric corrosion, but hydrogen sulfide and carbon dioxide do not, (Ref. 10.3). Twenty-year tests at several marine, industrial and rural sites have shown that atmospheric attack on aluminum takes place principally in the first year and progresses very slowly beyond the second year, (Ref. 10.4). Even at high temperatures in dry atmospheres, aluminum is highly resistant to most common gases, except the halogens, (Ref. 10.2).

In aqueous environments, corrosion resistance of aluminum is greatest under neutral or slightly acid conditions, where the protective oxide film is most stable (pH 5.5-8.5 at room temperature, 4.5-7 at 95C), (Refs. 10.1 and 10.5). Strong alkalies and strong-nonoxidizing acids destroy the oxide and greatly accelerate corrosion. Pitting attack occurs in waters containing chloride or other halogen ions, particularly at crevices or stagnant areas where passivity breakdown is accelerated by differential aerative effects. Traces of copper, iron and mercury ions are also effective in promoting localized attack via galvanic cells formed between aluminum and metal deposited by replacement reactions, (Ref. 10.1). Since aluminum is strongly anodic to most other common metals, galvanic coupling with them generally produces severe attack on the aluminum, especially in sea water, (Ref. 10.2).

Aluminum and its alloys are rather resistant to most molten salts. However, molten metals generally attack aluminum, particularly zinc and tin, which form alloys, (Ref. 10.2). Even a small amount of mercury is especially harmful, since it breaks down passivity and amalgamates, causing rapid perforation of aluminum piping or sheet, (Ref. 10.1). Under some conditions aluminum exhibits very poor resistance to chlorinated solvents and may even react explosively with them; however, such solvents, when properly inhibited, may be used for cleaning and degreasing without harm, (Ref. 10.6).

Aluminum purity significantly affects its corrosion resistance. High purity metal is more resistant than commercially pure aluminum, which in turn is generally more resistant than most alloys, (Ref. 10.1). Corrosion resistance of specific alloys is affected by composition, heat treatment and stress conditions, as discussed further below.

10.2 Aluminum-Magnesium-Silicon Alloys. The aluminum-magnesium-silicon alloys, such as 6061, contain magnesium and silicon in a ratio which forms a magnesium silicide compound. These alloys also contain small amounts of such elements as copper, manganese, chromium, zinc and titanium. The compositions were formulated to enhance certain characteristics such as strength, formability, etc. without affecting resistance to corrosion. Magnesium and silicon in solid solution, in the ratio of the compound Mg_2Si, do not affect the electrode potential of the alloy as shown in Table 10.1 for 6061 alloy. Thus these alloys have good resistance to corrosion, similar to commercially pure aluminum, (Ref. 10.7).

10.3 Behavior of 6061 Alloy. The 6061 alloy exhibits the best corrosion resistance of the heat treatable aluminum alloys. It has a high resistance to rural atmospheres and good resistance to weathering in industrial and marine atmospheres. Also, corrosion resistance of this alloy is independent of temper. The degree and nature of attack in other environments is influenced by factors such as severity of environment, temperature, etc. Extensive information does not appear to be available on the resistance of 6061 to various chemicals and compounds. The alloy has been used successfully for many years, however, in the construction of equipment for processing or handling industrial chemicals as listed in Table 10.2. The alloy is attacked by severe environments such as aqua regia, hydrochloric acid, hydrofluoric acid, lithium hydroxide, perchloric acid, potassium cyanide, potassium and sodium hydroxide and various mercury compounds. The 6061 alloy exhibits excellent resistance to stress-corrosion cracking in the O and T6 tempers, and there is no known instance of failure due to stress corrosion in service or in laboratory tests, (Ref. 10.10). The alloy may be susceptible to stress corrosion in the T4 temper if a high heat treating temperature is employed, followed by a slow quench. In the T6 temper, the aging precipitate is present in a random pattern as small particles which result in immunity to stress corrosion cracking. A study was made of high velocity projectile penetrations of simulated propellant tanks made from 6061-T3 sheet. Its purpose was to determine the impact sensitivity of this alloy in contact with liquid and solid rocket propellants. Thickness of tank walls was varied from 0.020 to 0.125 inch. Projectiles used were primarily 0.219 inch diameter spheres of steel, and impacts were made at velocities of 5800 feet per second. It was found that no interaction occurred between the 6061-T3 tank wall and the liquid oxygen (lox) propellant. Also, no chemical reaction occurred between the 6061-T3 and hydrazine (N_2H_4) or the solid propellants Arcite 373 and Hercules CLW. (High velocity impacts, however, did cause ignition of the Hercules CLW propellant), (Ref. 10.11).

10.4 Protective Measures. Under normal conditions and ordinary environments, 6061 alloy needs no surface protection. For more severe environmental conditions, clad material may be used for many applications. A common cladding material used is the 7072 aluminum alloy. Clad alloys have the corrosion resistance of the cladding material employed. Surface protection is discussed in greater detail in Chapter 11.

TABLE 10.1

Source	Ref. 10.7
Property	Electrode Potential vs 0.1 N Calomel at 25C
	(Aqueous solution of 53 gr NaCl and 3 gr H_2O_2 per liter)
Al + Mg + Si (1% Mg_2 Si solid solution)	-0.83 volt
6061-T4	-0.80 volt
6061-T6	-0.83 volt
Clad 6061	-0.96 volt
Aluminum (99.5%)	-0.85 volt

TABLE 10.2

Source	Ref. 10.9
Alloy	6061-T6
Information	Use of Alloy in Chemical Industries
Process or Chemical	Equipment
Acetic acid	Storage tank cars, condensers, piping
Acetic anhydride	Tank cars, heat exchangers, reaction vessels
Ammonium nitrate	Ammonia tanks, evaporators, tank cars
Ammonium hydroxide	Absorbers, condensers, piping
Edible oils and fats	Deodorizers, bleachers, filters
Fatty acids	Trays, filter presses, melting vessels
Formaldehyde	Scrubbers, tanks, drums
Glue and gelatin	Vats, evaporators, tanks, screens
Naval stores	Stills, condensers, receivers, tanks
Refrigerants	Compressers, heat exchangers, tubing
Ammonia, Carbon dioxide, Freons, Soda Ash manufacture	Heat exchangers, piping, absorbers
Water (distilled)	Storage tanks, receivers, degasifiers
Glycerin	Tank cars
Nitric acid	Tank cars

CHAPTER 10 - REFERENCES

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CHAPTER 11

SURFACE TREATMENTS

11.1 General. A wide variety of surface treatments can be applied to the 6061 alloy (and other aluminum alloys) to protect and improve the appearance of the surface. These include mechanical, chemical and electrochemical finishes and organic, porcelain and paint coatings. Alclad forms of aluminum alloys have a very high inherent resistance to corrosion and may be used without benefit of protective coatings, (Ref. 11.1).

11.2 Alclad Products. 6061 alloy is available as Alclad sheet and plate which consists of bare 6061 core material clad with a thin coating of 7072 alloy on both sides. The clad material is metallurgically bonded to the core material. It is chosen to provide a surface having a high resistance to corrosion and sufficiently anodic to the 6061 core to afford electrochemical protection to it in corrosive environments. Consequently, any spot of attack can penetrate only as deep as the core alloy where further progress is stopped by cathodic protection. Corrosion is thus confined to the clad material only. The life of the cladding is a function of its thickness and the severity of the environment. Alclad products, therefore, limit corrosion to a relatively thin clad surface layer, (Ref. 11.2).

11.3 Mechanical Finishes. Mechanical finishes are used to alter the texture of the alloy surface to provide a more decorative appearance or as a treatment prior to other finishing such as painting. Grinding, polishing and buffing result in smoother reflective surfaces. Abrasive blasting (sand or grit) gives a rough, matte finish which is often used as a base for organic coatings. Scratch finishing, satin finishing, Butler finishing and skin finishes are scratched line finishes which remove minor surface defects and provide a decorative effect. Mechanical methods remove the original heavy oxide film. For this reason mechanically finished parts are often given a protective coating by anodizing or lacquering. The possibility of generating an explosive mixture of fine powder and air during mechanical finish operations should be recognized, (Ref. 11.3).

11.4 Anodizing. Anodic coatings are hard, abrasion and corrosion resistant oxide coatings. The alloys can be anodically coated in a number of electrolytes, but most commercial anodizing is done by either the sulfuric acid or chromic acid process. The thickness of the coating is dependent upon the anodizing time. Coatings produced by the sulfuric acid process vary in thickness from 0.0001 to 0.001 inch. Coatings produced in chromic acid vary from 0.00001 to 0.00009 inch. Anodic coatings provide good protection against corrosion and are excellent bases for paint coatings, (Ref. 11.1).

11.5 Chemical Finishes. Chemical finishes are of three main types. Finishes used for decorative effects include caustic etching, acid etching and chemical polishing. Etched surfaces have a matte appearance while chemically polished surfaces are highly reflective and require protection by anodizing or lacquering. Conversion coatings can be oxide, phosphate or chromate types and are used primarily as base coatings prior to application of organic coatings. Miscellaneous special-purpose finishes includes those produced by the Alrok process, Modified Bauer-Vogel process and processes for staining aluminum alloys.

11.6 Electropolishing. This process produces a highly reflective surface and is often used for surface preparation prior to microscopic examination of metallurgical structure, see Chapter 3.

11.7 Electroplating of aluminum alloys has gained increase commercial use in recent years. A commonly used finish consists of successive deposits of copper, nickel and chromium. Other metals may be applied over the copper. Several etching methods produce a satisfactory base surface for electroplating. Also used is a method involving the immersion of the aluminum part in a solution of sodium zincate of controlled composition. Brass, iron, silver or chromium can be applied directly over this zinc immersion coating, (Ref. 11.4).

11.8 Painting. When severe conditions of exposure are to be encountered, it is frequently desirable to protect aluminum alloy surfaces with paint. Prior to painting, the surface should be properly prepared before priming. Dirt may be removed by brushing and grease or oil may be removed by means of solvent or degreasing techniques. The parts are then immersed in (or swabbed with) a solution of phosphoric acid and organic grease solvents diluted with water. A number of proprietary solutions of this type are available commercially. Solution temperature should be between 50 and 90F and contact with the metal part should not be for less than 5 minutes. The part is then rinsed with water and dried thoroughly. Where chemical treatment is impractical, mild sandblasting methods may be employed. Anodic or chemical conversion coatings form excellent bases for organic paint coatings. A zinc chromate primer, per MIL-P-8585 or equivalent, is recommended. Primer is applied to all surfaces and allowed to dry. For severe conditions of exposure, both primer and joint compound should be used at joints.

All surfaces except contacting surfaces may be given a second coat of paint consisting of two pounds of aluminum paste pigment (ASTM Spec. D962, Type II, Class B.) per gallon of varnish which meets Federal Spec. TT-V-86b, Type II or equivalent. The final assembled structure may be finished with one coat of aluminum paint. One or more coats of alkyd base enamel (pigmented to desired color) may be substituted for aluminum paint, (Ref. 11.5).

11.81 To minimize stress-corrosion cracking when alloy is subjected to sustained surface stresses and corrosive environments, certain surface treatments and protective coatings are effective. The most effective protection is obtained by applying a topcoat of epoxy-polyamide paint to shot-peened or metallized surfaces of the alloy. Satisfactory temporary protection is obtained by an electroplated galvanic coating (3 to 4 mils thick), or a topcoat of paint containing epoxy-polyamide or polyurethane resins. The former is preferred and can be used on unprimed surfaces. Care is necessary to prevent breaking or scratching the paint film. Shot peening alone will provide good surface protection (if all surfaces are treated) when corrosive environment is not severe. Anodic films and zinc-rich paints are the least effective coatings for preventing stress-corrosion cracking, (Ref. 11.6).

11.9 Porcelain Enameling. The principal difference between porcelain enameling of aluminum alloys and other metals is the use of porcelain frits, which melt at lower temperatures. High lead frits are commonly used and they can be formulated in a wide variety of colors and surface finishes. The enamel slip is sprayed onto chemically cleaned and treated surfaces and then fired at temperatures of 950 to 1050F for a period of 4 to 8 minutes, (Ref. 11.7).

CHAPTER 11 - REFERENCES

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CHAPTER 12

JOINING TECHNIQUES

12.1 General. The 6061 alloy can be readily joined by fusion and resistance welding techniques, by brazing and by riveting or bolting, Specifications that apply to the welding of aluminum alloys are listed in Table 12.1.

12.2 Welding. Reliable, sound, high quality welds have been made in aluminum alloys for many years. Although aluminum is a readily weldable metal, it has individual characteristics which must be well understood for successful welding of the metal or its alloys. Four important factors that must be considered are the low melting point, the presence of an oxide film, low strength at elevated temperatures, and the fact that aluminum exhibits no characteristic color changes even at temperatures up to the melting point. The welding of aluminum alloys requires care to prevent excessive melting of the material. The oxide film must be removed and prevented from reforming by some inhibiting technique before a good bond can be obtained. Temperatures must be controlled by measurement rather than judged by appearance of the alloy at elevated temperatures, (Ref. 12.2).

The 6061 alloy exhibits good welding characteristics, when proper procedures are used, in most tempers and products when welded by any of the presently used fusion and resistance welding procedures. The excellent corrosion resistance of the alloy does not appear to be lowered significantly by welding processes. Thus 6061 is an excellent choice for moderate strength welded structures requiring high corrosion resistance.

12.21 Fusion Welding. Aluminum alloy 6061 may be fusion welded by either the inert-gas-consumable electrode (MIG) or the inert-gas tungsten-arc (TIG) methods. The filler metal most commonly used for general purpose welding of this alloy is 4043 aluminum alloy, which results in weld zones having medium ductility and excellent resistance to cracking, (Ref. 12.3). Another filler metal that is sometimes employed in the fusion welding of this alloy is 5356 aluminum alloy. Fillerless fusion techniques are not recommended because of high cracking tendency.

The combined effect of porosity and mismatch has been studied for TIG welded 6061-T6 sheet, (Ref. 12.5). These studies have led to the conclusion that both mismatch and porosity contribute to the lowering of tensile strength of welded joints as the level of each increases in magnitude. This effect is shown in Fig. 12.1. Another study has indicated that there is very little depreciation of properties up to 50 percent mismatch. At 100 percent mismatch, however, an appreciable decrease in the strength of welded material was observed as shown in Fig. 12.2. All specimens in this study failed at the edge of the weld or in the annealed zone areas which do not respond to aging, (Ref. 12.6). Data obtained in this study on tensile properties of MIG and TIG welded sheet is presented in Table 12.3. These data indicate that automatic processes were definitely superior to manual TIG welding. They also indicate that repair welding may lead to a loss in strength and the degree of loss is dependent upon the number of repairs. In another study, however, semi-automatic MIG weld repairs on 6061-T6 plate were repeated up to 6 times with little observed effect. No thermal treatment was applied subsequent to welding or repair welding. The only evidence of an effect of rewelding was a slight loss in tensile strength of the plate at distances of 1/2 and 1 inch from the weld for 2 or more rewelds. The effect of the heat due to welding did not extend more than 1 1/2 inches from the weld centerline. The filler metal employed in this study was the 5356 alloy.

The effect of test temperature on tensile properties of TIG butt-welded sheet is illustrated in Figs. 12.3 and 12.4. Typical stress-strain curves for both unwelded and TIG welded sheet are shown in Fig. 12.5. Bulge test results for T4 and T6 TIG welded sheet are presented in Fig. 12.6. Metal thickness ranges for various weld procedures are given in Table 12.2.

The effect of welding speed on the tensile strength of weld specimens is shown in Fig. 12.7. These data indicate that the strength is increased as the weld speed becomes larger, and the strength approaches the base metal strength at high weld speeds.

12.22 Electrical Resistance Welding. Resistance welding (spot welding and seam welding) is a most useful and economic method of joining aluminum alloys. The welding process is almost entirely automatic and standard welding machines are capable of handling a wide variety of operations. Resistance welding heats only a small area of metal for a short length of time, thereby producing a narrow heat affected zone. Consequently, base material properties are not significantly affected.

Mechanical or chemical cleaning of the contact surfaces is necessary to obtain good spotwelds in aluminum as no fluxes are used during spotwelding. In aircraft construction, it is recommended that the contact resistance of the elements to be joined be continually checked as a measure of surface cleanliness. Surface contact resistance should not exceed 50 microhms for best results. Details on surface cleaning are given in Ref. 12.3.

The 6061 alloy, in all heat treated tempers, can be successfully spotwelded but special practices are required, and the range of machine settings is rather narrow. Precleaning is necessary for sound consistent welds. In the annealed condition the alloy is somewhat difficult to weld and spot welding in this condition is not recommended. Spot welded 6061 alloy has excellent resistance to corrosion in all tempers. Aluminum alloy 6061 may be joined by spotwelding to 1100, 3003, 5052, 2014, 2024, 7075, Clad 2014, Clad 2024, Clad 7075 and to itself (6061), (Refs. 12.3 and 12.8). The choice of the type of resistance welding machine for spot or seam welding of aluminum alloys depends partly on the power supply, its voltage drop characteristics, demand limitations and other similar factors. A more detailed discussion of resistance welding is given in Ref. 12.3.

12.221 Mechanical Properties of Spot Welds. The use of spot welds on military structural parts is governed by the requirements of the procuring or certificating agency, (Ref. 12.8). The requirements for equipment, materials and production control of spot and seam welds is covered by military specification MIL-W-6858B-1, see Table 12.1.

The minimum distance suggested for joint overlap and spot weld spacing is presented in Table 12.4 for a number of sheet thicknesses. The minimum allowable edge distance for spot welded joints is given in Table 12.5. Table 12.6 gives design shear strength allowables for spot welds in bare and clad alloys; the thickness ratio of the thickest sheet to the thinnest outer sheet in the combination should not exceed 4:1. In applications of spot welding where ribs, intercostals or doublers are attached to sheet, either at splices or at other points on the sheet panels, the allowable ultimate strength of the spot welded sheet should be determined by multiplying the ultimate tensile sheet strength (Mil-Hdbk-5 "A"values where available) by the appropriate efficiency factory as given in Fig. 12.8. The minimum values of the basic sheet efficiency in tension should not be applied to seam welds. Allowable tensile strength values for spot welded sheet less than 0.020 inch should be established on the basis of tests acceptable to the procuring or certificating agency, (Ref. 12.8).

The fatigue strength of triple-row spot welded lap joints is shown in Figs. 12.9 and 12.10 for sheet in the T6 Condition.

12.3 Brazing. The 6061 alloy exhibits excellent brazeability in the T4 and T6 Conditions and is generally brazeable by all commercial procedures and methods. The recommended brazing alloy is Alcoa 718 used in conjunction with flux number 33 or 34. Flux No. 33 is normally used for torch or furnace brazing and flux No. 34 is employed for dip brazing. The optimum brazing temperature range is 1080-1095F. Specifications on brazing flux and filler metals are listed in Table 12.7. Strong brazed joints depend on correct procedures, starting with clean surfaces. All oil and grease must be removed. Chemical cleaning is usually required and several proprietary cleaners are commercially available for this purpose. Mechanical processes such as wire brushing may also be used. Parts should generally be brazed within 48 hours after cleaning. All brazing operations require flux and the operation depends upon capillary action to draw filler metal into the joint. Clearances for flow of metal and escape of flux should be considered in the design of the joint as entrapped flux is a potential corrosion hazard.

The actual brazing temperature in most cases should be high enough to melt all of the filler metal. This is best determined by trial, using a thermocouple to measure the temperature.

A number of brazing techniques are used, depending upon the particular application. Among these are:

Torch brazing (oxyacetalyne etc.)
Furnace brazing
Dip brazing
Specialized processes (such as mechanized flame, induction brazing, block brazing and metal dip brazing).

A detailed discussion of these processes and the brazing of aluminum alloys is found in Ref. 12.9.

12.4 Riveting. Riveting is a commonly used method for joining aluminum, particularly the heat treatable alloys. It is reliable because riveting is a method that is well understood and highly developed. Also, modern riveting methods are largely independent of the operators skill and thus uniformity of riveted joints can be readily attained, (Ref. 12.2). Specifications for aluminum riveting are presented in Table 12.8.

12.41 Aluminum alloy rivets are preferred for the fabrication of aluminum alloy structures, although cold-driven annealed steel rivets have been used successfully for some applications. To determine the strength of riveted joints, it is necessary to know the strength of the individual rivet. The average shear strength for driven rivets of various aluminum alloys is given in Table 12.9. In most cases, such joints fracture by shearing, by bearing or tearing failure of the sheet or plate. It is customary to use a slightly larger factor of safety for the shear strength of rivets than is employed for other parts of an assembly. The design of joints where rivets are subjected to tensile loads should be avoided. Bolted connections may be used where high tensile stresses preclude the use of riveting. Information in greater detail on the riveting of aluminum alloys is given in Refs. 12.10 and 12.11. Design data on mechanical joints using rivets or bolts may be found in Mil-Hdbk-5, (Ref. 12.8).

TABLE 12.1

Source	Ref. 12.1, 12.12, 12.13, 12.14			
Item	Welding specifications			
Product or process	Federal	Military	ASTM	AMS
Weldments (aluminum and aluminum alloys)	-	MIL-W-22248	-	-
Welding of aluminum alloys	-	MIL-W-8604	-	-
Welding (aluminum alloy armor)	-	MIL-W-45206	-	-
TIG welding, aluminum alloy for structures	-	MIL-W-45205	-	-
Welding; resistance, aluminum alloys	-	MIL-W-45210A	-	-
Welding; spot, seam or stitch(Al, steel, Mg and Ti)	-	MIL-W-6858B	-	-
Welding rods (aluminum)	QQ-R-566-2	-	B285-61T	4190A 4191A
Welding electrodes (flux coated)	-	MIL-E-15597C	B184-43T	-
Welding electrode wire	-	MIL-E-16053J	B285-61T	-
Flash welds (rings, flanges)	-	-	-	7488A

METAL THICKNESS RANGES FOR COMMERCIAL WELDING PRACTICE

TABLE 12.2

Source	Ref. 12.3		
Alloy	Weldable Aluminum Alloys		
Welding Method	Min. Thickness (in)		Max. Thickness (in)
	Experimental	Practice	
Fusion welding (MIG)	0.032	0.093	(a)
Fusion welding (TIG)	0.025	0.051	1.0
Gas	0.025	0.051	1.0
Atomic hydrogen	0.025	0.051	1.0
Metal-arc	0.064	0.125	(a)
Spot	-	foil	3/16 (b)
Seam	foil	0.010	3/16

(a) No limit imposed by welding process. Most experience to date has been on pieces up to 3 inches thick.

(b) Experimental procedures have been developed for metal up to 0.5 inches thick.

TENSILE PROPERTIES OF TIG AND MIG WELDED SHEET

TABLE 12.3

Source		Ref. 12.6											
Alloy		6061-T4											
Test		Tensile Properties of Welded Sheet											
Thickness, in		0.050						0.125					
Data		F_{tu}, ksi		F_{ty}, ksi		e, %		F_{tu}, ksi		F_{ty}, ksi		e, %	
Orientation		L	T	L	T	L	T	L	T	L	T	L	T
Weld Process	Condition												
Manual TIG	Aged to T6	27.3	26.9	22.0	21.5	2.8	2.2	28.1	29.0	20.3	20.3	5.6	3.8
Automatic TIG	Aged to T6	43.1	42.3	38.8	37.2	6.7	7.0	50.1	50.2	46.8	45.4	8.3	9.8
(a)	Aged to T6	39.4	39.1	36.3	36.1	3.4	3.4	37.1	33.0	33.9	27.5	3.0	3.2
(b)	Aged to T6	38.0	35.5	35.3	32.7	2.2	2.0	33.5	32.7	27.5	27.1	4.0	4.0
MIG Welds	Aged to T6	-	-	-	-	-	-	42.0	41.9	39.2	38.3	3.9	4.0
(c)	Aged to T6	-	-	-	-	-	-	35.2	36.3	30.4	32.4	3.0	3.0
(d)	Aged to T6	-	-	-	-	-	-	32.4	32.7	25.7	26.8	3.5	3.8

(a) Automatic TIG welded plus one repair weld.
(b) Automatic TIG welded plus two repair welds.
(c) MIG welded plus one repair weld.
(d) MIG welded plus two repair welds.

Each value is average of 6 tests.
4043 filler wire was used for all welds
Aging treatment: 340-355F, 8 hours
After welding, no solution treatment was employed.

TABLE 12.4

Source	Ref. 12.3	
Alloy	Aluminum Alloys	
Data	Suggested minimum joint overlap and spacing of spot welds	
Thinnest sheet in joint, inch	Minimum joint overlap, inch	Minimum weld spacing, in
0.016	5/16	3/8
0.020	3/8	3/8
0.025	3/8	3/8
0.032	1/2	1/2
0.040	9/16	1/2
0.051	5/8	5/8
0.064	3/4	5/8
0.072	13/16	3/4
0.081	7/8	3/4
0.091	15/16	7/8
0.102	1	1
0.125	1 1/8	1 1/4

TABLE 12.5

Source	Ref. 12.8
Alloy	Aluminum Alloys
Property	Minimum allowable edge distances for spot-welded joints (a)(b)(c)

Nominal thickness of the thinner sheet, in	Edge distance, E, in
0.016	3/16
0.020	3/16
0.025	7/32
0.032	1/4
0.036	1/4
0.040	9/32
0.045	5/16
0.050	5/16
0.063	3/8
0.071	3/8
0.080	13/32
0.090	7/16
0.100	7/16
0.125	9/16
0.160	5/8

(a) Intermediate gages will conform to the requirement for the next thinner gage shown.

(b) Edge distances less than those specified above may be used provided there is no expulsion of weld metal or bulging of the edge of the sheet or damage to bend radii by electrode.

(c) Values may be reduced for non-structural applications or applications not depended on to develop full weld strength.

TABLE 12.6

Source	Ref. 12.8			
Alloy	Aluminum Alloys. (bare and clad)			
Property	Spot weld maximum shear strength standards (a)			
Nominal thickness of thinner sheet, inch	Material ultimate tensile strength, lb.			
	Above 56 (ksi)	28 to 56 (ksi)	20 to 27.5 (ksi)	19.5 ksi and below
0.012	60	52	24	16
0.016	86	78	56	40
0.020	112	106	80	62
0.025	148	140	116	88
0.032	208	188	168	132
0.040	276	248	240	180
0.050	374	344	321	234
0.063	539	489	442	314
0.071	662	578	515	358
0.080	824	680	609	417
0.090	1002	798	695	478
0.100	1192	933	750	536
0.112	1426	1064	796	584
0.125	1698	1300	840	629
0.160	2490	-	-	-
0.190	3230	-	-	-

(a) The reduction in strength of spotwelds due to cumulative effects of time-temperature-stress factors is not greater than the reduction in strength of the parent metal.

SPECIFICATIONS ON BRAZING FLUX AND FILLER METAL

TABLE 12.7

Source	Ref. 12.9
Specification	Specifications on Brazing Flux and Filler Metal
ASTM B260 and AWS-A5.8	Tentative Specification for Brazing Filler Metal
AMS 3412	Flux-Aluminum Brazing (Alcoa No. 33)
AMS 4184A	Aluminum Alloy Brazing Wire (No. 716)
AMS 4185	Aluminum Alloy Brazing Wire (No. 718)
AMS 4190A	Aluminum Alloy Welding Wire (4043)

TABLE 12.8

Source	Ref. 12.1		
Item	Specifications for Rivets (Aluminum)		
Products	Specifications		
	Federal	Military	AMS
Rivets	FF-R-556a	MIL-R-1150A-1	7220C
	-	MIL-R-5674B-1	7222C
	-	MIL-R-12221B	7223
Rivets, blind	-	MIL-R-7885A-1	-
	-	MIL-R-8814-1	-
	-	MIL-R-27384	-
Rivet, wire	QQ-A-430-1	-	-

TABLE 12.9

Source	Ref. 12.10		
Data	F_{su} (Average) for Driven Rivets (c)		
Alloy and Temper before Driving (a)	Driving Procedure	Alloy and Temper after Driving	F_{su} (Aver) (ksi)
1100-H14	Cold, as received	1100-F	11
2017-T4	Cold, as received	2017-T3	39
2017-T4	Cold, immediately after quenching	2017-T31	34(b)
2024-T4	Cold, immediately after quenching	2024-T31	42(b)
2117-T4	Cold, as received	2117-T3	33
5056-H32	Cold, as received	5056-H321	30
6053-T61	Cold, as received	6053-T61	23
6061-T4	Cold, immediately after quenching	6061-T31	24(b)
6061-T4	Hot, 990 to 1050F	6061-T43	24(b)
6061-T6	Cold, as received	6061-T6	30
7277-T4	Hot, 850 to 975F	7277-T41	38

(a) These designations should be used when ordering rivets.

(b) Immediately after driving, the shear strengths of these rivets are about 75% of the values shown. On standing at ambient temperatures, they age harden to develop full shear strength. This action takes about 4 days for 2017-T31 and 2024-T31 rivets. Values shown for 6061-T31 and 6061-T43 rivets are attained in about 2 weeks. Values of 26 ksi are attained by 6061-T31 rivets about 4 months after driving. Values shown for 7277-T41 rivets are attained in about one week.

(c) These values are for rivets driven with core point heads. Rivets driven with head requiring more pressure may be expected to develop slightly higher strengths.

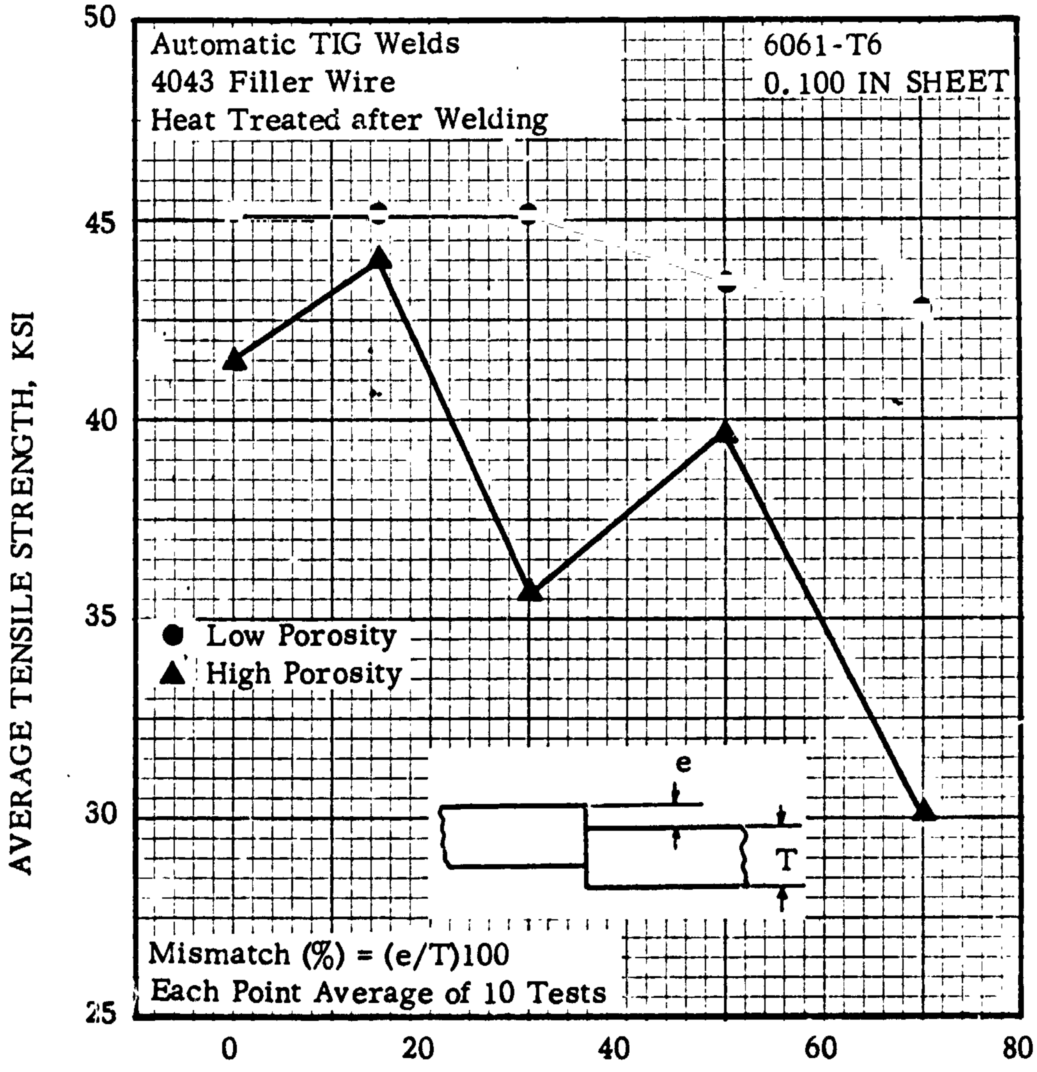

FIG. 12.1 COMBINED EFFECT OF POROSITY AND MISMATCH FOR TIG WELDED SHEET

(Ref. 12.5)

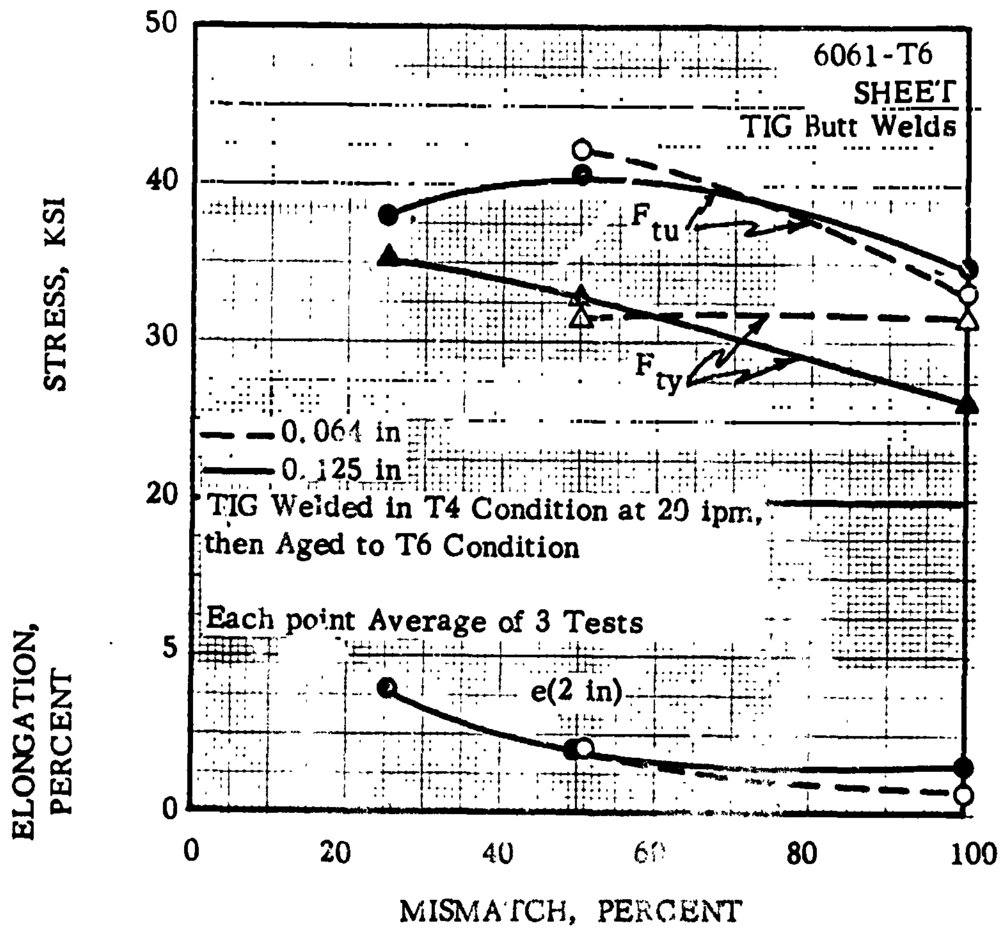

FIG. 12.2 EFFECT OF MISMATCH ON TENSILE PROPERTIES OF TIG WELDED SHEET

(Ref. 12.6)

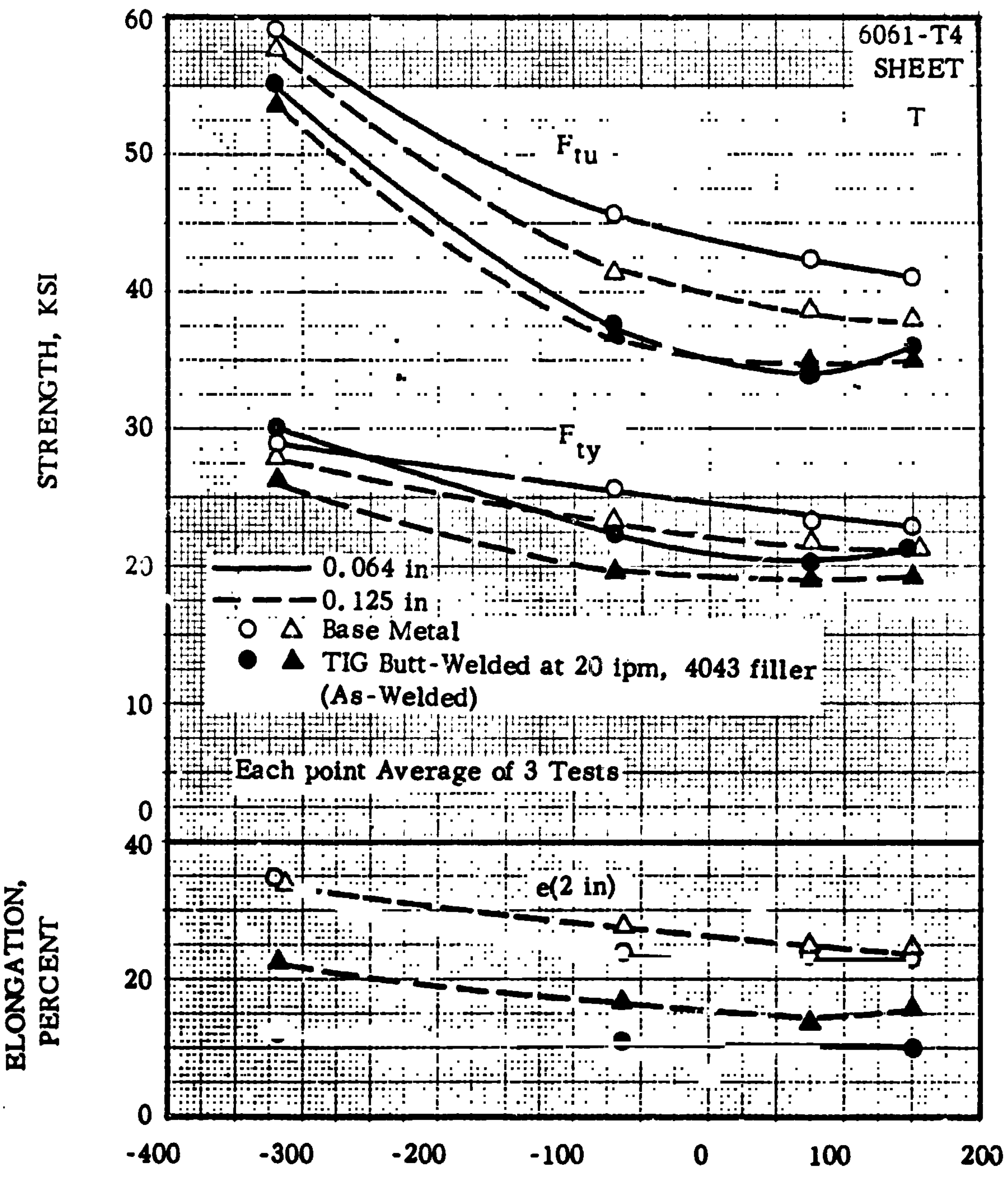

FIG. 12.3 EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF TIG BUTT-WELDED SHEET IN T4 CONDITION

(Ref. 12.6)

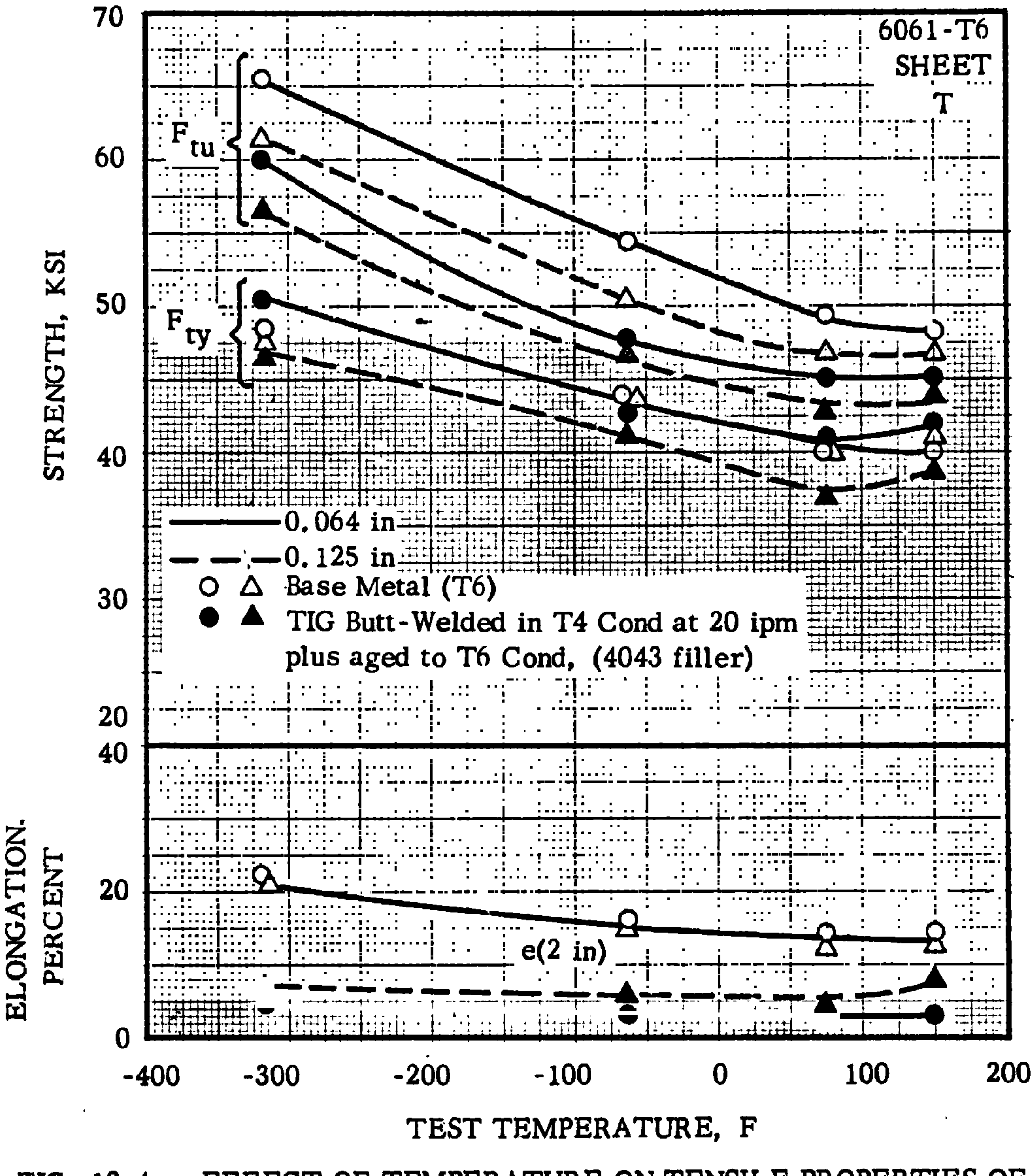

FIG. 12.4 EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF TIG BUTT-WELDED SHEET (IN T4 CONDITION) AGED TO T6 CONDITION

(Ref. 12.6)

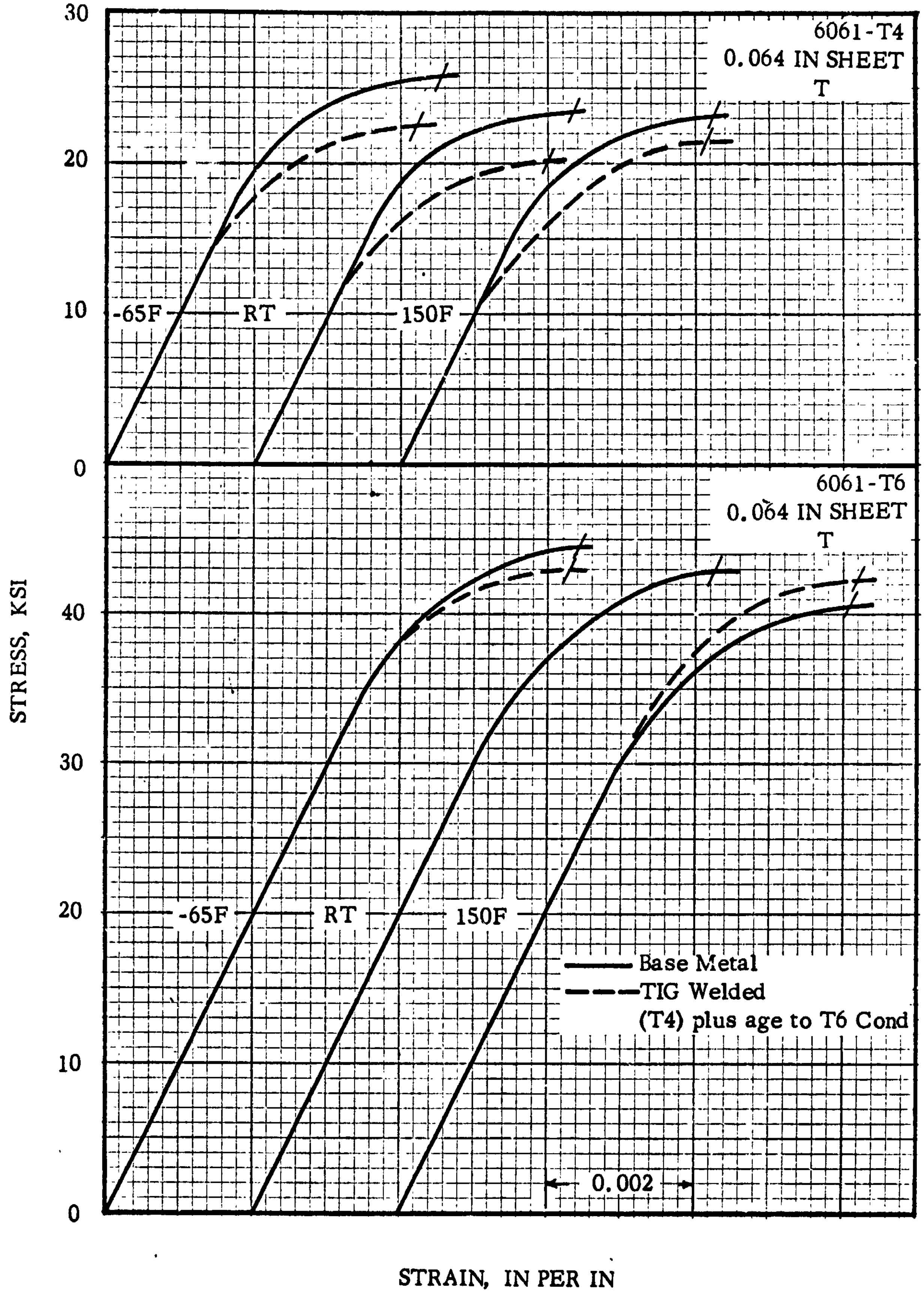

FIG. 12.5 TYPICAL STRESS-STRAIN CURVES FOR UNWELDED AND TIG WELDED SHEET AT VARIOUS TEMPERATURES

(Ref. 12.6)

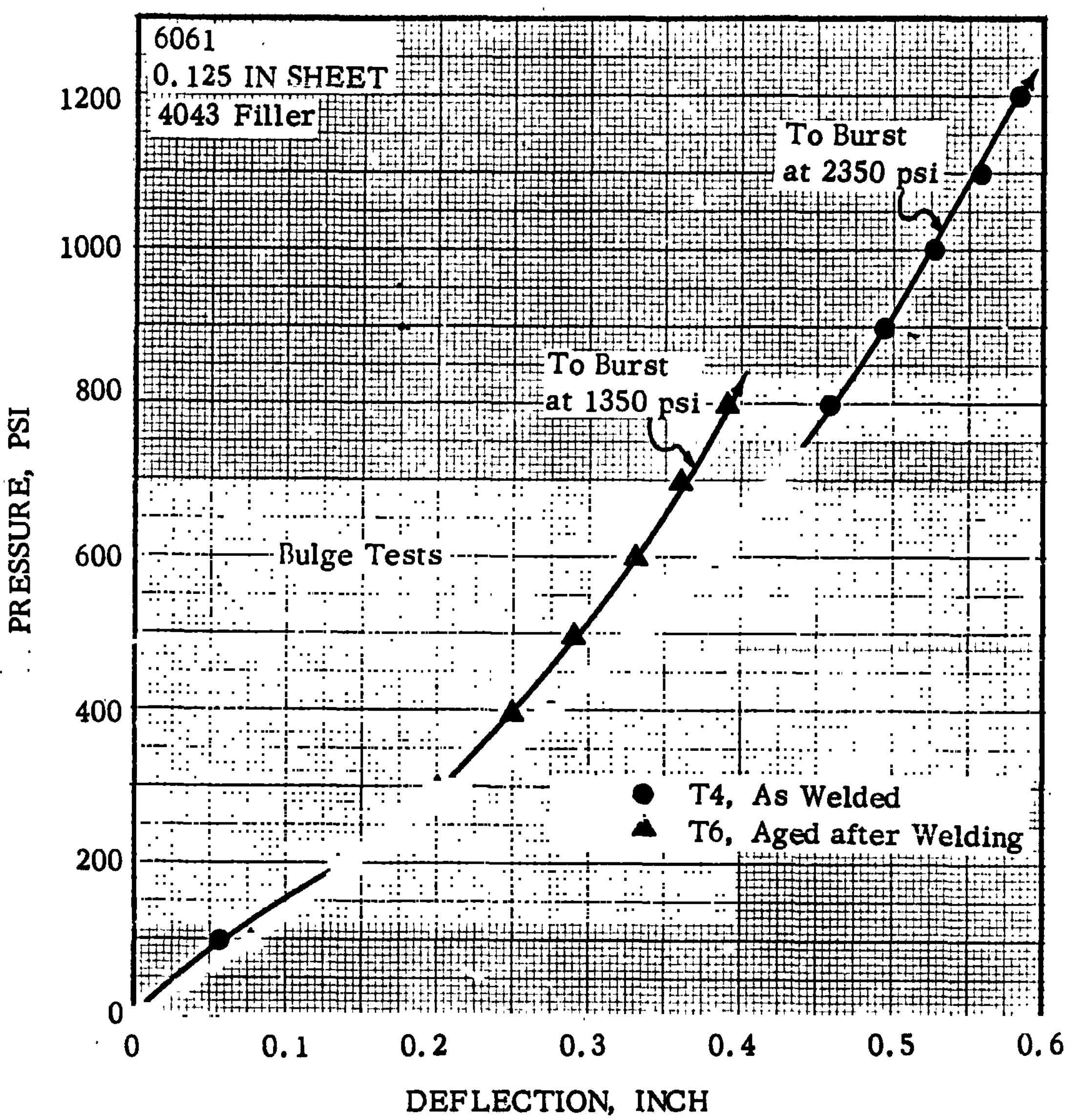

FIG. 12.6 BULGE TEST RESULTS FOR T4 AND T6 TIG WELDED SHEET (Ref. 12.6)

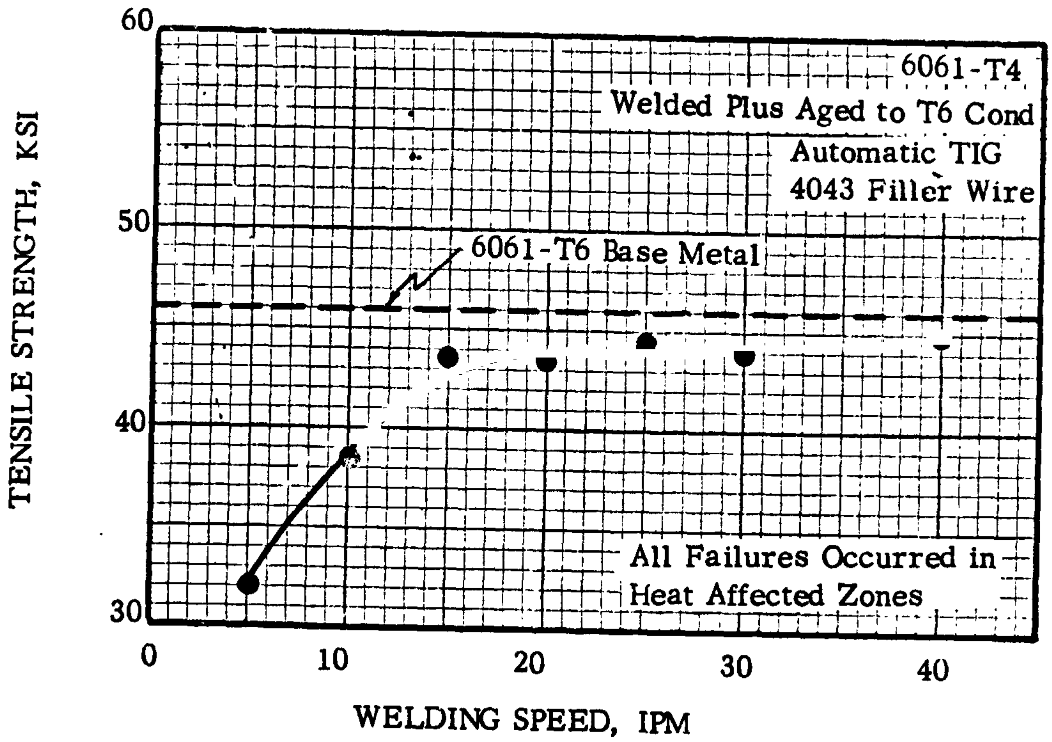

FIG. 12.7 EFFECT OF WELDING SPEED ON TENSILE STRENGTH OF WELD SPECIMENS

(Ref. 12.7)

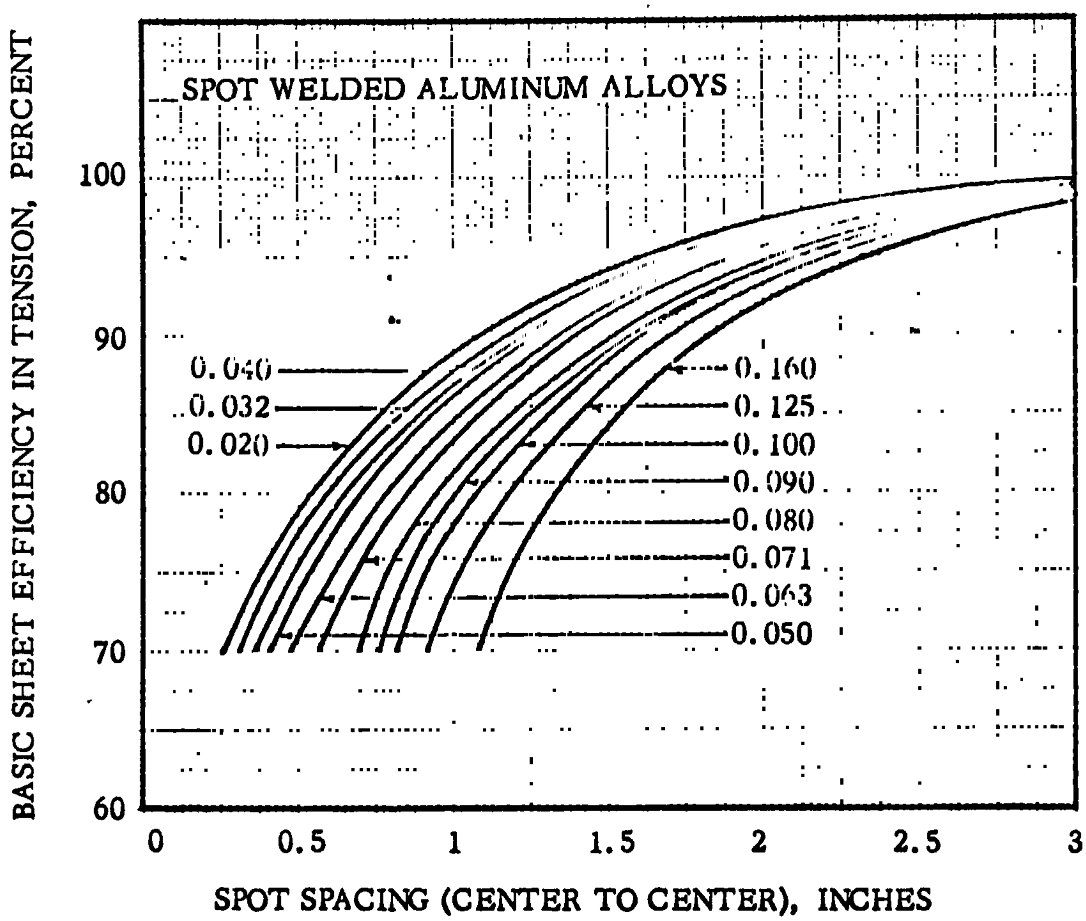

FIG. 12.8 EFFICIENCY OF THE PARENT METAL IN TENSION FOR SPOT WELDED ALUMINUM ALLOYS

(Ref. 12.8)

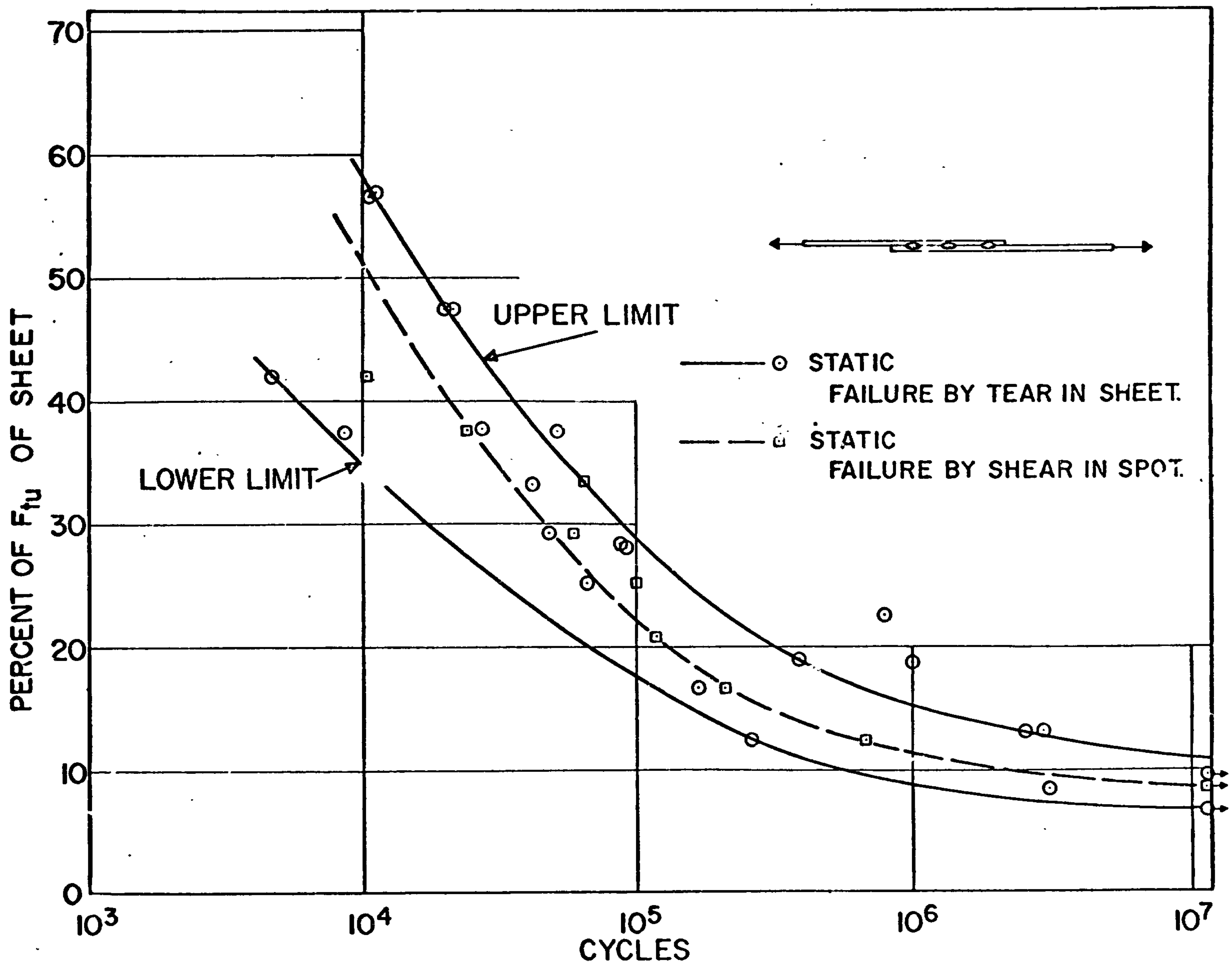

FIG. 12.9 FATIGUE STRENGTH OF TRIPLE ROW SPOT WELDED LAP JOINTS IN 6061-T6 ALUMINUM ALLOY SHEET. LOAD RATIO = 0.05.

(Ref. 12.8)

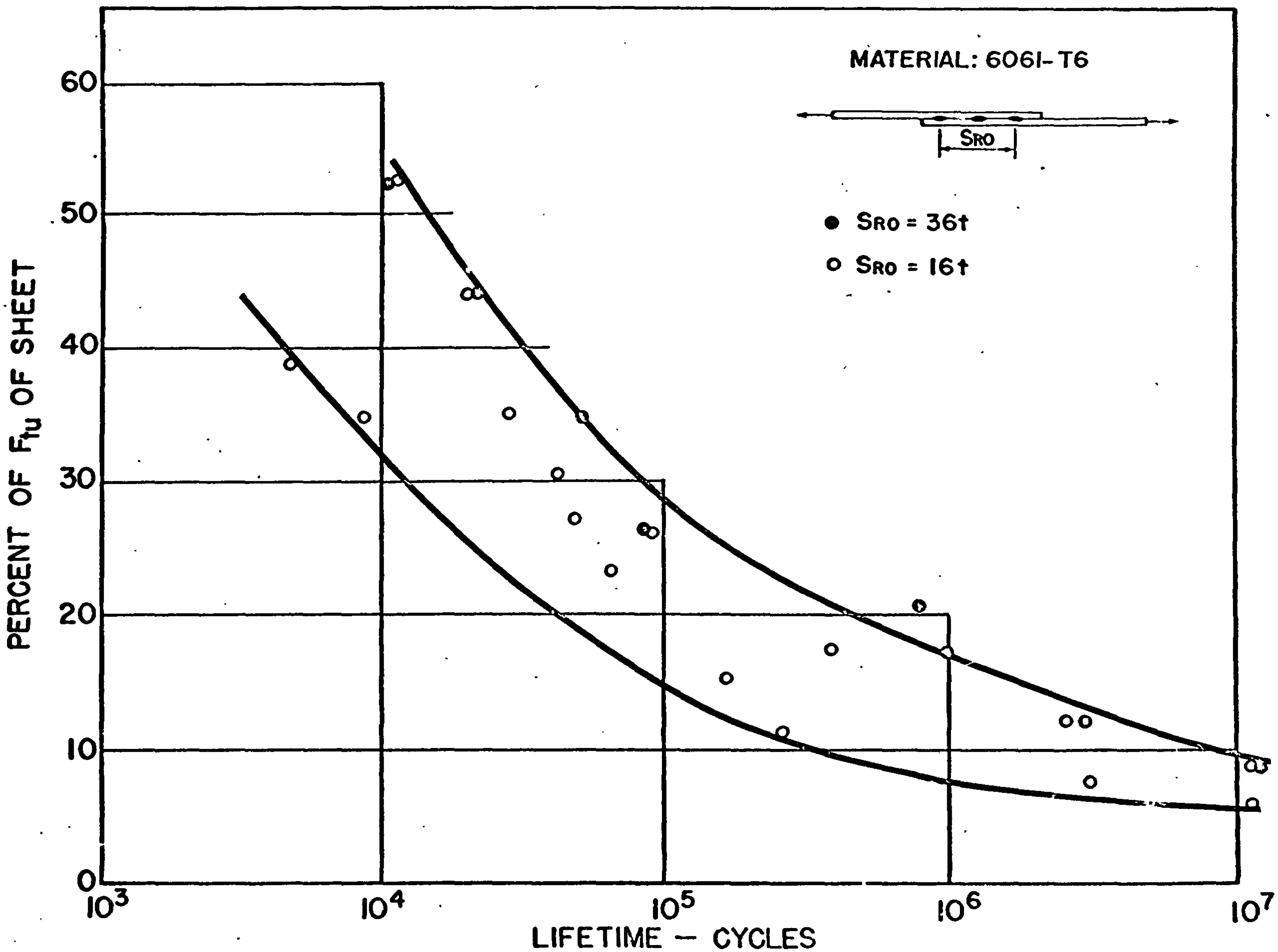

FIG. 12.10 FATIGUE STRENGTH OF TRIPLE ROW SPOT WELDED LAP JOINTS. LOAD RATIO = 0.5 (STATIC FAILURE BY TEAR IN SHEET).

(Ref. 12.8)

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